EFFECTS OF VARIOUS ARCHITECTURAL PARAMETERS ON SIX ROOM ACOUSTICAL MEASURES IN AUDITORIA

By

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A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1994

ACKNOWLEDGEMENTS

Enormous efforts from numerous people have made the undertaking of this project possible. I wish to express my sincere appreciation to all of the people who have contributed.

This project required the development of a measurement method to document architectural features from drawings. Prof. Siebein and "Ganpat" initiated this method and students taking a University of Florida graduate acoustics class with Professor Seibein and me in the fall of 1992 helped to measure the room data. Martin Gold, Gary Madaras, Antonio Carvralio, Carlos Jiminus, Loren Raia, John Kidwell, and Michael Gisler all deserve special thanks for refining the method and measuring the architectural data in numerous halls. Professor Siebein, Richard P. Cervone, and Gary Madaras together took the acoustical measurements in the rooms included in the present study. Cervone and Maradas processed a large portion of the accoustical data besides what I did. Carlos Jiminus helped to organize acoustical data for me. Dr. Anders Gade of the Danish Technical Institute shared with me his experience of conducting a similar study. Many tasks of this project could have not been accomplished without his initial work.

All my supervisory committee members, Dr. David M. Green, Dr. Harold Doddington, and Prof. Bertram Kinzey Jr., have enthusiastically assisted me in many

way ranging from instrumentation and statistics to my writing skill. Prof. William Weismantel and Prof. Gary W. Siebein, as chairman and cochairman of my committee, should receive special gratitude for their enthusiasm, patience, expertise and support.

Most of all, I want to thank my parents for always being there for me. I could not have gone through the last few months without their support.

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Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirement for the Degree of Doctor of Philosophy

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April, 1994

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The effects of architectural parameters on six room acoustical measures were investigated by means of correlation analyses, factor analyses and multiple regression analyses based on data taken in twenty halls. Architectural parameters were used to estimate acoustical measures taken at individual locations within each room as well as the averages and standard deviations of all measured values in the rooms.

The six acoustical measures were Early Decay Time (EDT10), Clarity Index (C80), Overall Level (G), Bass Ratio based on Early Decay Time (BR(EDT)), Treble Ratio based on Early Decay Time (TR(EDT)), and Early Inter-aural Cross Correlation (IACC80). A comprehensive method of quantifying various architectural characteristics of rooms was developed to define a large number of architectural parameters that were hypothesized to effect the acoustical measurements made in the rooms.

This study quantitatively confirmed many of the principles used in the design of concert halls and auditoria. Three groups of room architectural parameters such as the parameters associated with the depth of diffusing surfaces were significantly correlated with the hall standard deviations of most of the acoustical measures. Significant differences of statistical relations among architectural parameters and receiver specific acoustical measures were found between a group of music halls and a group of lecture halls. For example, architectural parameters such as the relative distance from the receiver to the overhead ceiling increased the percentage of the variance of acoustical measures that was explained by Barron's revised theory from approximately 70 % to 80 % only when data were taken in the group of music halls

This study revealed the major architectural parameters which have strong relations with individual acoustical measures forming the basis for a more quantitative method for advancing the theoretical design of concert halls and other auditoria. The results of this study provide designers the information to predict acoustical measures in buildings at very early stages of the design process without using computer models or scale models.

CHAPTER 1

INTRODUCTION

At the end of the nineteenth century, diagrams of sound rays were used by Tuthill to study the behavior of direct and reflected sound in rooms he designed such as Carnegie Hall. He suggested that echoes would occur at the seats in the front part of a hall when the width and height of the room are both large (Tuthill, 1946). After almost a century, only a few studies have been conducted to expand the knowledge of quantitative relations among a broad range of architectural parameters and important acoustical measures.

> After about four decades of work, subjective room acoustic research has now reached a state of maturity in which many aspects of the listening experience in concert halls can be described quite well by objective parameters . . . but hitherto their use in practical design has been hampered by the fact that many of them can only be predicted using extensive scale- or computer models, and only rather few ideas about their general behavior exist or have been documented. (Gade, 1990, p. E 4-8-1).

Gade suggested the importance of understanding the relations between architectural parameters and acoustical measures now that people have come to a general agreement on what acoustical measures should be used in the study of room acoustics. The current study was proposed to investigate such relations among a large number of architectural parameters and several well accepted acoustical measurements made in rooms.

A number of acoustical measures derived from impulse responses of specific source-receiver paths in the rooms have been proposed by researchers in the past thirty years. These researchers have attempted to define how people hear and what physical and environmental factors determine a person's subjective perception of a number of acoustical qualities, particularly the qualities people prefer for listening to music in an auditorium (Siebein, 1986). Rarely were the results of this recent research integrated as a part of the design process of rooms because quantitative relations among the details of architectural characteristics of rooms and these acoustical measures were not available. Scale or computer models have to be used to know how acoustical measures are affected by changes in the shape of halls on a case by case basis. If the details of architectural characteristics of rooms can be quantitatively defined as a number of parameters, these relations can be obtained by statistical analyses based on both acoustical and architectural data taken in a large number of halls (Gade, 1989).

In the past decade, a few studies have been conducted to find out the relationships among a small number of architectural parameters and acoustical measures based on data taken in a large number of halls. A set of fourteen fundamental architectural parameters have been used in a series of studies conducted by Gade since 1988. Several specific relations were found among these fundamental architectural parameters and spatial means of acoustical measures (Gade, 1988; Gade, 1991). A study was conducted by Barron and Lee to examine how well their revised theory for concert halls can describe the measured values of acoustical measures by comparing the magnitude of correlations among three groups of halls (Barron, 1988).

Another study presented by Hook suggested significant relations among acoustical measures taken inside a hall and source-receiver distances measured in different ways (Hook, 1990).

The implementation of these studies in the design of actual halls was limited because: 1) the details of the architectural characteristics in large halls can not be simply represented by a small number of architectural parameters, and 2) the effects of room architectural parameters and the effects of the source-receiver paths were rarely considered together. However, the studies mentioned above initiated the methods of investigating the relationships among architectural parameters and acoustical measures based on a statistical approach.

The objective of the current study was to expand upon these previous studies with a more detailed set of architectural parameters where the architectural characteristics and the source-receiver paths were both considered. The statistical relations among architectural parameters and acoustical measures were examined by correlation analyses, factor analyses, and multiple regression analyses.

Architectural parameters were developed primarily based on various characteristics that have been suggested to affect the acoustical quality of rooms. Special attention was given to developing architectural parameters beyond those which were previously used by Gade, Barron, Hook and Bradley because many characteristics mentioned above have not yet been transformed to quantified parameters in these studies.

This study was expected to reveal the major architectural parameters which have strong relations with individual acoustical measures as the first step in advancing the theoretical design of concert halls and other auditoria. This is important because the acoustical qualities of a room are determined to a large extent by the initial design concept. The results of this study allow one to consider how basic architectural design decisions will effect acoustical measures in a room very early in the design process using simple formulas. The results of the study inevitably depend on the selection of the halls. Direct implementation of the findings must be limited to halls with architectural parameters fall within the ranges of parameters measured in this study.

CHAPTER 2

STATISTICAL ANALYSIS METHODS

The objective of the current study was to expand upon the previous studies made by Gade, Barron, Hook, and Bradley with a more detailed set of architectural parameters where the architectural characteristics and the source-receiver paths were both considered. The statistical approaches used by these researchers were used in the current study.

Analysis Procedures

The relationships among architectural parameters and acoustical measures were investigated by means of correlation analyses, factor analyses and multiple regression analyses. Room architectural parameters, the architectural parameters describing the architectural characteristics of the hall, were used to estimate the hall averages and the hall standard deviations of acoustical measures based on acoustical measurements taken at multiple receiver locations in each of the halls. Next, the analyses were repeated. Receiver architectural parameters, the architectural parameters describing the receiver locations, and the interactions of among the two types of architectural parameters were used to estimate acoustical measures made at individual locations within the rooms. Figure 2-1 illustrates the conceptual diagram of the analyses procedures.

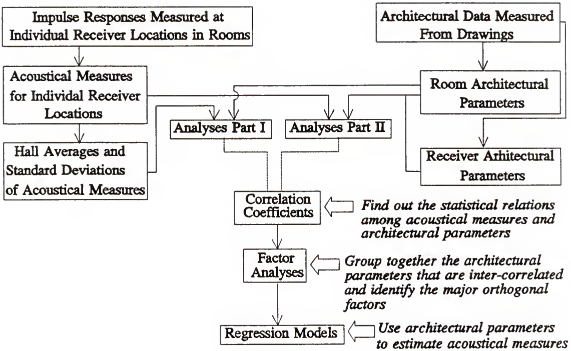
Impulse Responses Measured at Individual Receiver Locations in Rooms
Architectural Data Measured From Drawings
Acoustical Measures for Individal Receiver Locations
Room Architectural Parameters
Analyses Part I
Analyses Part II
Hall Averages and Standard Deviations of Acoustical Measures
Receiver Arhitectural Parameters
Correlation Coefficients
Find out the statistical relations among acoustical measures and architectural parameters
Factor Analyses
Group together the architectural parameters that are inter-correlated and identify the major orthogonal factors
Regression Models
Use architectural parameters to estimate acoustical measures

Figure 2-1. Conceptual diagram of the analyses procedures.

Correlation Coefficients and Factor analyses

Correlation coefficients among architectural parameters and acoustical measures were studied before multiple regression procedures were performed. The correlation coefficients were compared with those found in the literature review. In addition to the analyses of correlation coefficients, factor analyses were used to identify groupings of architectural parameters. The groupings were important because significant correlations may exist among architectural parameters when there were a large number of parameters relative to the number of observations. For instance, if all of the hall halls have similar widths and heights but different lengths, the length could be significantly correlated with the room volume. For the architectural parameters that were grouped together as one factor, the author intended to put more emphasis on those which were previously found to be important by other researchers.

Latent roots larger than one was used as the factor selection criteria. Rotation of factors based on the Varimax rotation method was used to perform orthogonal groupings of the variables.

Multiple Regression

Multiple linear regression models were presented to study the combined effects of architectural parameters on individual acoustical measures. The regression models were calculated using the SAS software package.

Architectural parameters used as regressors were selected among the parameters that were significantly correlated with individual acoustical measures at the 95 % (or 98 %) level. These architectural parameters were selected to represent individual orthogonal factors. The selected representative parameters for individual factors were generally the ones that have been previously suggested by other researchers. When several architectural parameters can be used to represent a factor, these parameters were used in turn to derive separate regression models. For example, parameter A, parameter B, and parameter C were all significantly correlated with acoustical measure x. The factor pattern shows that parameters A and B were grouped together as one factor and C as the other. Two regression models may be presented if either the effect of parameter A or the effect of parameter B can be reasonably explained. One model would contain parameter A and parameter C and the other would contain parameter B and parameter C.

A Forward Selection procedure was used to calculate regression models because the procedure started by adding the most important regressor and this regressor would remain in the model throughout the procedure. A 95 % or greater significance level was used as the variable entry criterion for the Forward Selection procedure.

Two criteria were used to evaluate the accuracy of the models. The model R square represents the percentage of variance explained by the model. The standard deviation (STD) of residuals represents the magnitude of the differences between the estimated value and the observed value. The results of these two criteria were compared to the values presented previously by Gade.

The standard deviations of residuals were also compared to the average confidence intervals of individual observations of the six acoustical measures. This comparison was made to determine if the regression models reach the possible limit of accuracy based on the given data of acoustical measures. It is not necessary to derive more accurate models if the standard deviations of residuals of the models are small relative to the confidence intervals. The unexplained variance can be considered as random errors in this case.

According to the empirical rule with the assumption of a normal distribution, four times the STD of residuals was expected to represent the 95% range of the residues. Therefore, the 95 % range of the residuals was compared with the average 95 % confidence interval. The 95 % confidence intervals for all acoustical measures are presented in Chapter 3 after the six acoustical measures are defined.

The Halls Investigated

The halls investigated included eight concert halls, three multi-use halls used in the concert mode, eight lecture halls and three churches. Table 2-1 summarizes the twenty-two halls and associated data.

The halls were selected nearly randomly. The selection was, however, biased by geographic location. A few architectural characteristics that may appear in other large halls do not exist in the halls investigated:

1. No halls have downward slanting sidewall sections near the ceiling that can direct lateral sound rays from the stage into the audience area.
2. No halls have the audience areas that are divided into small stepped sections of vineyard or terraced seating enclosed by sound reflective panels to introduce early lateral reflections

The lecture halls were generally small with no seats on the stage. They typically had only one audience floor. The ceiling or walls were partially covered by absorbent panels. In the analyses based on acoustical measures at individual receiver locations, the eight lecture halls were used as one sub-group and the other halls were used as the other sub-group.

Table 2-1. List of the twenty two halls and associated data.

Hall		Reverberation Time in sec. - Avg. of 500 Hz & 1 kHz	Room Volume in cu.ft.	Seating Capacity in seat	Hall Characteristics
Concert Halls					
O1	Meyerhoff Hall, Baltimore	2.05	756,558	2,465	D,2B,2S,O
O2	Symphony Hall, Boston	2.40	670,579	2,555	R,2B,2S
O3	Kleinhans Hall, Buffalo	1.58	644,000	2,839	F,1B
O4	Orchestra Hall, Detroit	1.65	577,676	2,038	PF,2B,1S
O5	Concert Hall, Kennedy Center, D.C.	1.66	763,501	2,759	R,3B,3S
O6	Academy of Music, Philadelphia	1.17	554,861	2,914	H,3B,3S
O7	Severance Hall, Cleveland	1.55	554,000	1,996	PF,2B,1S
O8	Troy Saving Bank Hall, Troy	2.31	399,778	1,097	R,2B,O
Multi-Use Halls					
M1	Festival Hall, Tampa	2.06	764,611	2,493	RF,3B,3S,O
M2	Florida Theater, Jacksonville	1.19	378,866	1,980	PF,1B
M3	Ruth Eckerd Hall, Clearwater	2.05	516,782	2,199	D
Churches					
C1	Methodist Church, Gainesville	1.41	119,339	450	R,1B,G
C2	Annie Pfeiffer Church, Lakeland	1.23	75,921	580	F,1B,G
C3	West Side Baptist Church, Gainesville	1.19	100,099	717	F,1B
Lecture Halls					
L1	Aerospace Dept. (303), UF, Gainesville	0.53	14,109	54	SQ
L2	Architecture (411), UF, Gainesville	1.02	6,775	54	SQ
L3	Architecture (423), UF, Gainesville	1.24	9,327	100	R,AC
L4	Carleton Auditorium, UF, Gainesville	2.24	147,032	640	R
L5	Chemistry Auditorium, UF, Gainesville	1.04	48,325	306	R
L6	Fine Arts (105), UF, Gainesville	1.78	21,000	123	PF
L7	Turlington Hall (L007), UF, Gainesville	1.96	57,920	302	F
L8	Little Hall (109), UF, Gainesville	0.87	20,236	173	PF,AC

F: Fan-Shaped Plan
PF: Partial Fan-Shaped Plan
D: Diamond Shape Plan
RF: Reverse Fan-Shaped Plan
H: Horse-Shoe Shaped Plan
R: Rectangular Plan
SQ: Square-Shaped Plan

1B: 1 Balcony
2B: 2 Balconies
3B: 3 Balconies

1S: 1 Level of Side Boxes
2S: 2 Levels of Side Boxes
3S: 3 Levels of Side Boxes

O: Overhead Panels over Stage
G: Gable Ceiling
AC: Absorbent Ceiling

CHAPTER 3

ACOUSTICAL MEASURES

In the past thirty years, various acoustical measures have been proposed in an attempt to define a person's perception of a number of acoustical qualities. Recently, people have come to a general agreement regarding five or six primary features that contribute to the overall impression of music listening in an auditorium. In the current study, six acoustical measures were used to represent the factors recently suggested by Barron, Cervone and Beranek (Cervone, 1991; Beranek, 1992).

Theoretical Basis

Table 3-1 summarizes the six acoustical measures, the associated subjective meanings and definitions. All of the acoustical measures except IACC80 were derived from $p(t)$, the sound pressure measured using a microphone at a location in a hall. The notation t designates time with the origin ($t = 0$) chosen to be the arrival of the wide band direct pulse.

Early Decay Time, EDT10

Early Decay Time is a modified measure of Reverberation Time. Reverberation Time is the time required for a sound to decay 60 dB whereas the Early Decay Time is the time required for the first 10 dB of decay multiplied by 6 to extrapolate the result to a 60 dB decay. Early Decay Time was proposed by Jordan based on previous research that suggested, as described by Cremer and Muller, "the later part of a reverberant decay excited by a specific impulse in running speech or music is already masked by subsequent signals once it has dropped by about 10 dB". (Cremer and Muller, 1982). A study by Cervone showed a significant relation between Early Decay Time and subjective overall impression (Cervone *et al*, 1991).

Table 3-1. The six acoustical measures used in the study

Acoustical Measure	Subjective Meaning	Definition	
Early Decay Time	Reverberation/Clarity	$EDT=6(E^{-1}(10)-E^{-1}(0))\mathrm{sec.}$	where $E^{-1}(d)$ is the inverse function of $E(t)$ and $E(t)$ represents the sound decay as a function of time
Early to Late Energy Ratio	Clarity	$C_t=10\log\frac{\int_0^t p^2(t)dt}{\int_t^\infty p^2(t)dt}$	where t=80 ms is used, this measure is referred to as "Clarity" or "Clarity Index"
Strength / Overall Level	Loudness	$G=10\log\frac{\int_0^\infty p^2(t)dt}{\int_0^\infty p_A^2(t)dt}$	where $p_A(t)$ is the sound pressure measured in an anechoic chamber corrected to a distance of 10 m.
Bass Ratio based on Reverberation Time	Timbre: Warmth	$BR(RT)=\frac{RT_{125Hz}+RT_{250Hz}}{RT_{500Hz}+RT_{1kHz}}$	
Treble Ratio based on Reverberation Time	Timbre: Brilliance	$TR(RT)=\frac{RT_{2kHz}+RT_{4kHz}}{RT_{500Hz}+RT_{1kHz}}$	
Inter-aural Cross Correlation	Spaciousness or Diffuseness	$IACC_t=\frac{\int_0^t p_L(t)p_R(t+\tau)dt}{(\int_0^t p_L dt\int_0^t p_R dt)^{\frac{1}{2}}}$	where $p_L(t)$ and $p_R(t)$ designate the sound pressures measured at the entrances of the left and right eardrums, with the listener facing the source. The variable τ is from -0.5 to 0.5 ms, which is roughly the time difference between the arrival of a wave at the two ears from the right side or left side of the head. When t=80 ms is used, this measure is referred to as "Early Inter-aural Cross Correlation".

Clarity Index, C80

Clarity Index (also called Clarity or Clearness Index) is a specific measure of the Early to Late Energy Ratio. The sound energy integrated from 0 ms to 80 ms is used as the early energy while the rest of the energy is used as the late energy. This measure was developed by Reichardt based on 1) the suggestion by Theile that the distinctness of speech was dependent upon the levels of "useful" sound energy, the energy integrated from $t = 0$ ms to $t = 50$ ms, relative to the total sound energy and 2) the observation of music by Reichardt that led to a widely accepted value of 80 ms as the limit of perceptibility of music (Cremer and Muller, 1982). However, C80 has been found to be significantly correlated with EDT10 (Cervone et al, 1991). This measure is also denoted as C or C_{80} in the literature.

Overall Level, G

Overall Level (also called Overall Strength) is the total energy of an impulse response at a location in a room relative to the total energy of the same source measured in an anechoic chamber at a distance of ten meters. This reference sound energy was first used by Gade and Rindel in 1985 (Gade, 1988). Overall Level was proposed to approximate the subjective sense of loudness. This measure is also denoted as L in the literature.

Bass Ratio Based on Early Decay Time, BR(EDT)

Bass Ratio Based on Early Decay Time was recently proposed by Beranek (Reverberation Time was originally used) to evaluate timbre or tonal balance, especially warmth (Beranek, 1962). It is measured by the ratio of (a) the sum of the

Early Decay Time at 125 Hz and 250 Hz to (b) the sum of the Early Decay Time at 500 Hz and 1 kHz.

Treble Ratio Based on Early Decay Time, TR(EDT)

Treble Ratio Based on Early Decay Time, defined by the author, is proposed to evaluate timbre or tonal balance, especially brilliance. It is measured by the ratio of (a) the sum of the Early Decay Time at 2 kHz and 4 kHz to (b) the sum of the Early Decay Time at 500 Hz and 1 kHz. This measure was developed because treble and bass have been evaluated separately in the questionnaires used in several major studies.

Early Inter-Aural Cross Correlation Coefficient, IACC80

The Inter-aural Cross Correlation is the normalized maximum cross correlation of the left-ear and right-ear sound pressures with the listener facing the sound source. This measure is referred to as Early Inter-aural Cross Correlation, $IACC_E$ or IACC80 if the integration time between $t = 0$ ms to $t = 80$ ms is used. Studies suggested that IACC80 is correlated with the subjective attribute of spaciousness (Ando, 1985; Beranek, 1992).

Instrumentation

The acoustical measurements used in this study were taken by the Architectural Technology Center at the University of Florida using the Acoustical Research Instrumentation for Architectural Spaces (ARIAS) system. Figure 3-1 represents the schematic diagram of the version of the ARIAS system used when the acoustical measurements included in this study were taken.

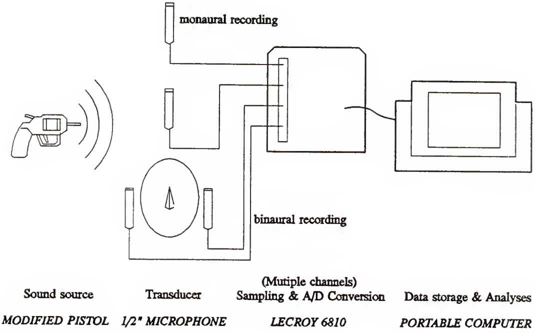

Figure 3-1. The schematic diagram of the version of ARIAS system when acoustical measurements used in this study were taken.

Impulse responses were acquired directly by recording a 0.38 caliber blank fired by a specially modified Remington pistol. Room acoustical measures were calculated in octave bands from 125 Hz to 4 kHz from the impulse responses.

The high energy output produces a sound pressure level of approximately 125 dB at 10 meters. In a large size auditorium, this level gives more than 35 dB of signal to noise ratio except in the 125 Hz octave band.

The sampling device of the current ARIAS system is a Lecroy module 6810. A sampling frequency of 50 kHz was used. This sampling frequency is twice as fast as the highest frequency that can be obtained by the B&K 1/2 inch diameter audio microphones. Therefore, a low pass/anti-aliasing filter was not used. Multiple channels can be recorded simultaneously on the Lecroy. Up to 8 channels were used for some field measurements conducted in this study. The A/D conversion is also performed on the Lecroy 6810 module which is used together with the Catalyst software package. The Lecroy module 6810 module contains a 12 bit successive converter. It provides a dynamic range of approximately 68 dB. This is sufficient for room acoustics study if the dynamic range can be properly used.

The ARIAS system also contains several software packages developed by Doddington and Schwab. They were programmed to convert the data format; to perform octave band filtering; to compute numerical acoustical measures; and to plot reflectograms. The current programs were written for Microsoft Windows operating system using the C++ language.

The microphones used for monaural and binaural recording is the B&K 4134 1/2 inch omni-directional microphones. Binaural measurements were always taken with the manikin facing the center front source on the stage no matter where the sound source was located or how the seat was oriented.

The locations of microphones used for binaural measurements varied because acoustical data used in this study were accumulated over a four year period. First, the microphones were located outside a real human head before the manikin was built two years ago. Once the manikin was constructed, the microphones were mounted in similar locations. When binaural measurements were taken using microphones inside the manikin head, the microphones were located at the end of the ear drums with a angle of approximately 70 degrees. A study suggested that very small differences existed between Early Inter-Aural Cross Correlations measured outside the manikin head and those measured inside the head (Madras et al, 1993).

In the field, acoustical measurements were measured at multiple receivers with a sound source on the center front of the stage. The center front sound source was located at the approximate location of the conductor in the concert halls, under the proscenium arch in the multi-use halls, at the location of the lectern in the churches, and at the location of the speaker in the lecture halls. The source was at an elevation of 5'6" above the floor. The number of receiver positions in each hall varied from two to fourteen in approximate proportion to the size of the hall. Figure 3-2 shows the plan sketch of the receiver locations and the center front sound source on the stage in Symphony Hall, Boston (hall O2).

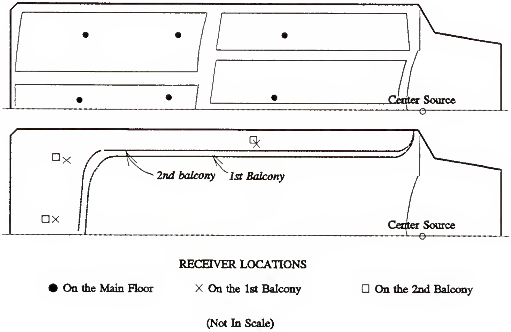

Figure 3-2. The plan sketch of the receiver locations and the center front sound source on the stage in Symphony Hall, Boston (hall O2).

All of the acoustical measures except IACC80 were measured in the 22 halls. IACC80 was not measured in four of the lecture halls.

Accuracy and Variations of Acoustical Data

The ARIAS system is similar to the instrumentation systems used by Bradley, Gade, and other researchers in Japan. A comparison of the ARIAS system with the system used by Gade and the one used by Bradley was made by taking measurements together in the eight concert halls. Close agreement of acoustical measures Early Decay Time (EDT10), Clarity Index (C80), Overall Level (G), and Early Inter-aural Cross Correlation (IACC80), particularly in the 500 Hz band and 1 kHz band, were found. Thus, the average values of acoustical measures at the 500 Hz and 1 kHz octave bands were used with the exception of the Bass Ratio based on EDT and Treble Ratio based on EDT. The Reverberation Time calculated based on the decay from 5 dB to 35 dB (or 25 dB) was not used in this study because significant differences of this acoustical measure were found among the three measurement systems (Bradley et al, 1993).

Standard Deviations of Measurement Error

Reproducibility of measurements at the same receiver position was calculated that included the variations among of pistol shots and changes of the source position of approximately 1 ft. The change of sound source position existed because the pistol was held by hand. This may be a shortcoming of the measurement procedure but the change of head position of an listener can be significant as well.

Table 3-2 summarizes the standard deviation due to measurement errors for each acoustical measure comparing the current data to the data presented by Gade and Bradley. The average of the standard deviations due to measurement errors of the 6 octave bands were used for all of the acoustical measures except BR(EDT) and TR(EDT). The standard deviations of EDT10 and C80 used in this study were not greater than those presented by Gade and Bradley. The large standard deviation of G can be attributed to variations in the loudness of the 0.38 blanks used in the pistol.

Table 3-2. Random errors for each acoustical measure comparing the current data to the data presented by Gade and Bradley.

	Sources of Error	EDT10 in sec.	C80 in dB	G in dB	BR(EDT)	TR(EDT)	IACC80
Current	Repeat (±0.5 ft.)	0.041	0.33	0.58	0.024	0.016	0.023
Gade	±30 cm	0.120	0.80	0.70			
Bradley	±30 cm		0.60	0.44			
	±10 cm		0.49	0.27			
	Repeat		0.22	0.13			

Table 3-3. The 1/4 of average values of 95 % confidence interval of acoustical measures taken at individual locations and the averages and standard deviations of all measured values in the rooms.

1/4 Average 95 % Confidence Interval	EDT10 in sec	C80 dB	G dB	BR(EDT)	TR(EDT)	IACC80
Hall Average	0.75	0.77	1.23	0.42	0.28	0.77
Hall Standard Deviation	0.042	1.17	1.99	0.022	0.012	0.164
@ Individual Receiver	0.055	0.36	1.09	0.027	0.022	0.036

Table 3-3 summarizes the 1/4 average 95% confidence interval of acoustical measures taken at individual locations and the averages and standard deviations of all measured values in the rooms. These values can be used to compare with the standard deviations (STDs) of residues of regression models presented in Chapter 5 and Chapter 6.

Hall Standard Deviation

The hall standard deviations of acoustical measures made in each hall were compared to the overall standard deviations of measures made in all halls. The hall standard deviation of each acoustical measure was calculated based on the acoustical measures at multiple receiver locations in a hall. This comparison was made to study the magnitude and variations of the hall standard deviations of acoustical measures. Detailed data are presented in Appendix A.

Figure 3-3 represents the maximum, minimum, and average hall standard deviations relative to the overall standard deviations of acoustical measures. The minimum relative hall standard deviation was similar among all acoustical measures. The smallest range of relative hall standard deviation was found for acoustical measure EDT10. There were significant differences between the relative maximum and minimum hall standard deviations. The significant differences suggested that the hall standard deviations of acoustical measures may be determined by room architectural parameters.

The average hall standard deviations of acoustical measures (represented by "■") varied from 22 % to 55 % of the overall standard deviations over the six acoustical measures. The magnitude of hall standard deviations suggested that acoustical measures taken at individual receiver locations may be determined by receiver architectural parameters.

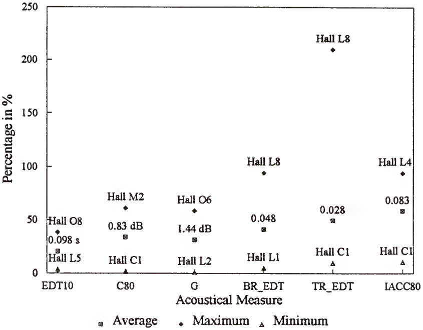

Figure 3-3. The maximum, minimum, and average hall standard deviations of acoustical measures relative to the overall standard deviations of acoustical measures.

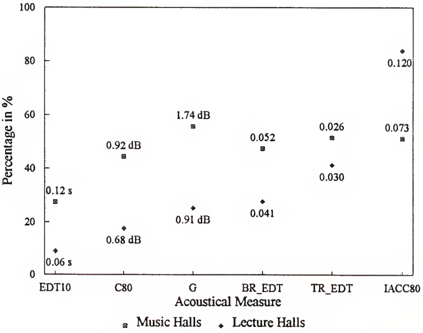

Figure 3-4. The average hall standard deviations of acoustical measures relative to the overall standard deviations taken in individual groups of halls comparing the music halls to the lecture halls.

Figure 3-4 represents the average hall standard deviations of acoustical measures relative to the overall standard deviations of acoustical measures taken in individual groups of halls comparing the music halls to the lecture halls. The relative hall standard deviations of acoustical measures were larger in the music halls than in the lecture halls for all of the acoustical measures except IACC80. This suggested that receiver parameters may be used to increase the explained percentage of the variance of the acoustical measures taken in the music halls.

CHAPTER 4

ARCHITECTURAL PARAMETERS

A special effort of this study was to determine what architectural parameters to use to relate with acoustical measures and how to measure these parameters. A comprehensive method of quantifying various architectural characteristics of rooms was developed based on various architectural characteristics that have been suggested to affect the acoustical quality of rooms. This method defined a large number of architectural parameters that were hypothesized a) to represent the actual design consideration of room acoustic qualities during the design of buildings and b) to quantify the major differences of architectural characteristics among the halls investigated in this study. The developed architectural parameters were, however, still not sufficient enough to describe some complex interior details such as the plaster ornaments in many of the old concert halls.

The Proposed Architectural Parameters

The architectural parameters can be categorized into three groups: 1) the room architectural parameters were the parameters defining hall characteristics, 2) the receiver architectural parameters were the parameters defining the characteristics of the specific receiver locations 3) the interaction parameters were the interactions among at least two of the above mentioned "raw" parameters. Table 4-1 summarizes all the architectural parameters used in the current study.

The calculated estimates for Reverberation Time (RT), Clarity Index (C80), and Overall Level (G) were also considered as architectural parameters because certain architectural parameters were required to calculate many of these estimations.

The interaction parameters were selected based on a literature search and pilot studies. Five types of interaction parameters were actually used in the analyses:

1. The parameters that defined the relations among the linear dimensions of each of the stage enclosure and the audience chamber enclosure such as Lmax/W (Maximum Audience Chamber Length / Average Audience Chamber Width);
2. The parameters that defined the ratios of the stage enclosure to the audience chamber enclosure such as the Hs/H (Average Stage Height / Average Audience Chamber Height);
3. the parameters that defined the ratios of the linear dimensions of major building elements such as Dub/Hub (Average Under-Balcony Depth / Average Under-Balcony Height).
4. the parameters that defined the relative locations of the receivers such as rc/RC (Distance to Overhead Ceiling / Average Distance to Overhead Ceiling); and
5. the interactions among the receiver architectural parameters and the room architectural parameters that did not define the relative receiver locations such x×Asc (x Coordinate of Receiver × Average Stage Ceiling Angle).

Table 4-1. List of architectural parameters used in this study.

Category		Term	Definition
Room Architectural Parameters	Volume and Seating Capacity	V	Room Volume
		Sa	Total Seating Area
		Sb	Balcony Seating Area
		Ss	Stage Floor Area
		$P\alpha$	Percentage of Ceiling and Wall Absorbent Surface
		N	Seating Capacity
		n	Number of balconies
	Room Envelope - Linear Dimensions	Lmax	Maximum Audience Chamber Length
		H	Average Audience Chamber Height
		W	Average Audience Chamber Width
		Ls	Stage Length
		Hs	Average Stage Height
		Hsr	Average Stage Roof Height
		Ws	Average Stage Width
	Room Envelope - Angles	Af	Average Main floor Slope
		Ac	Average Ceiling Angle of Audience Chamber
		Aw	Average Side Wall Angle of Audience Chamber
		Asc	Average Stage Ceiling Angle
		Asw	Average Stage Side Wall Angle
		Acp	Average Ceiling Panel Angle of Audience Chamber
		Awp	Average Side Wall Panel Angle of Audience Chamber
		Act	Average Ceiling Angle of Audience Chamber, Transverse Direction
		Actp	Average Ceiling Panel Angle of Audience Chamber, Transverse Direction
	Seat Distribution	X	Average x Coordinate of Receivers
		std(x)	STD of x Coordinate of Receivers
		|Y|	Average Absolute y Coordinate of Receivers
		std(|y|)	STD of Absolute y Coordinate of Receivers
		Z	Average z Coordinate of Receivers
		std(z)	STD of z Coordinate of Receivers
		R	Average Distance to Origin/Source
		std(r)	STD of Distance to Origin/Source
		A	Average Angle of Incidence
		std(a)	STD of Angle of Incidence
		|AH|	Average Absolute Horizontal Angle of Receivers
		std(|ah|)	STD of Absolute Horizontal Angle of Receivers
		RC	Average Distance to Overhead Ceiling
		std(rc)	STD of Distance to Overhead Ceiling
	Balcony Configuration	Dob	Average Over-Balcony Depth
		Dub	Average Under-Balcony Depth
		Hub	Average Under-Balcony Height
		Aub	Average Under-Balcony Ceiling Angle
		Dsb	Average Side Box Depth
		Hsb	Average Side Box Height
		Ksb	Side Box Design (Yes: 1; No: 0)
	Surface Roughness	Pcdl	Percentage of Diffusing Ceiling Surface, Longitudinal Direction
		Pcdt	Percentage of Diffusing Ceiling Surface, Transverse Direction
		Pwd	Percentage of Diffusing Wall Surface, Horizontal Direction
		Dcdl	Depth of Diffusing Ceiling Surface, Longitudinal Direction
		Dcdt	Depth of Diffusing Ceiling Surface, Transverse Direction
		Dwd	Depth of Diffusing Wall Surface, Horizontal Direction
		Lcdl	Length of Diffusing Ceiling Surface, Longitudinal Direction
		Lcdt	Length of Diffusing Ceiling Surface, Transverse Direction
		Lwd	Length of Diffusing Wall Surface, Horizontal Direction
		Lmcd	Maximum Panel Size of Audience Ceiling
		Lmwd	Maximum Panel Size of Audience Side Wall
	Surface Absorption	α	Average Absorption Coefficient (for random incidence)
		$BR(\alpha)$	Bass Ratio based on Average Absorption Coefficient
		$TR(\alpha)$	Treble Ratio based on Average Absorption Coefficient
		Kch	Chair type (Theater: 0; Tablet-arm: 1)

Table 4-1. (Continued)

Category		Term	Definition
Receiver Architectural Parameters		x	x Coordinate of Receiver
		|y|	Absolute y Coordinate of Receiver
		z	z Coordinate of Receiver
		r	Distance to the Origin/Source
		rc	Distance to the Overhead Ceiling
		a	Angle of Incidence
		|ah|	Absolute Horizontal Angle of Receiver
		av	Vertical Angle of Receiver
		rp	Distance to the Perimeter
Interaction Parameters	Interaction of Two Room Architectural Parameters	V/Sa	
		Sa/N	
		Sb/Sa	
		Sb/n	
		H/W	
		HW	
		Lmax/W	
		HW/Lmax	
		Ss/Sa	
		Ws/W	
		Ls/L	
		Hs/H	
		HsWs	
		HsWs/HW	
		Awp*W	
		(Dob+Dub)/2	
		Dub/Hub	
		Dub/Lmax	
		Hub/H	
		Kch*TR_α	
	Interaction between One Room Architectural Parameter and One Receiver Architectural Parameter	y/Y	
		r/R	
		z/H	
		rc/RC	
		(z-rc)/H	
		y*Dub	
		x*Asc	
		r*α	
		r/R*Dub	
		a*α	
		a*Dub	
		a*Y	
		a/H	
		$rp/(V^{1/3})$	
		rc/RC*Y	
Theoretical Estimates	Hall Average	RTs	Calculated Reverberation Time, Sabine Formula
		C80_edt	Calculated Hall Average of C80 Using EDT10
		C80_rts	Calculated Hall Average of C80 Using RTs
		G_edt	Calculated Hall Average of G Using EDT10
		G_rts	Calculated Hall Average G Using RTs
	At Individual Receiver Locations	C80b_edt	Calculated C80 Using EDT10, Barron's Formula
		C80b_rts	Calculated C80 Using RTs, Barron's Formula
		Gb_edt	Calculated G Using EDT10, Barron's Formula
		Gb_rts	Calculated G Using RTs, Barron's Formula

In the following statistical analyses, a few parameters listed in Table 4-1 were not used to minimize the total number of architectural parameters because the inter-correlations among parameters increased with a increase of the number the parameter. It is difficult to interpret the correlations among architectural parameter and acoustical measures if there are significant inter-correlations among architectural parameters. The architectural parameters were removed from the analyses either because they were highly correlated with other architectural parameters or they were developed primarily to calculate the interactions with other specific parameters. For example, parameter Sa/N (Total Seating Area / Seating Capacity) was included but Seating Capacity (N) was not because parameter N was found to be significantly correlated with Room Volume (V) and Total Seating Area (Sa).

Theoretical Basis

The architectural parameters were developed from three types sources:

1. Well accepted theoretical estimations of the acoustical measures (Barron, 1988).
2. The studies presented by Barron, Bradley, Hook, and Gade where similar statistical research approaches were taken (Barron, 1988; Bradley, 1989; Hook, 1989, Gade, 1990), and
3. Other studies and empirical design principles that revealed the acoustically important qualitative architectural characteristics or quantified architectural parameters. For instance, the angle between side wall panels was suggested to influence the lateral reflections (Marshall, 1989).

Theoretical Estimations

Theoretical estimations were incorporated in the study to examine how well these estimates predicted actual acoustical measures and what architectural parameters can be used to improve the accuracy of the estimates. Only the equations derived from a few well accepted theories were used in this study.

Diffuse Sound Field Theory

The diffuse sound field is defined as the sound field where 1) the amplitudes of the incident waves are distributed uniformly over all possible directions, 2) the phases of the sound waves are distributed at random so that interference effects can be neglected, 3) sound decay is purely exponential, and 4) sound energy is uniformly distributed in the space (Kuttruff, 1991).

Practically, halls can only be partially diffuse sound fields because: 1) all the absorption is concentrated at the floor where the seating areas are located 2) the sound source is generally at one end of the hall , and 3) the interior surfaces of halls are often not particularly diffusing. (Barron 1988).

Sabine's Reverberation Time and Absorption Coefficient (α). Sabine's Reverberation Time equation is still one of the most useful tools for acoustical design even though several revised equations have been proposed after W.C. Sabine did his experiments in early twentieth century (Sabine, 1927; Kuttruff, 1991). Calculated Reverberation Time based on Sabine's formula (RTs) and Surface Absorption Coefficient for Random Incidence (measured using the reverberation chamber method) (α) were used in the analyses. Calculated Reverberation Time (RTs) was determined by Room Volume (V) in cu.ft., Average Absorption Coefficient (α), Total Room Surface Areas (St) in sq.ft and Attenuation Coefficient due to molecular absorption of air (m) in ft^{-1}:

$$\text{RTs in sec.} = \frac{0.049 \times V}{\alpha St + 4mV} \tag{4-1}$$

Controlling the variation of reverberation among frequency was also considered by Sabine as a criteria for hall design. Bass Ratio Based on Absorption Coefficient (BR(α)) and Treble Ratio Based on Absorption Coefficient (TR(α)) were developed in this regard. Parameter BR(α) was expected to be correlated with acoustical measures Bass Ratio Based on Early Decay Time (BR(EDT)). Parameter TR(α) was expected to be correlated with acoustical measure Treble Ratio Based on Early Decay Time (BR(EDT)).

Clarity index and Overall Level. Clarity Index (C80) was calculated by Kurer in 1972 using Reverberation Time (RT) in sec. based on a purely exponential decay (Cremer and Müller, 1982).

$$\text{C80 in dB} = 10 \log (e^{1.104/RT} - 1) \tag{4-2}$$

Overall Level (G) was calculated by Barron using Reverberation Time (RT) in sec. and Room Volume (V) in m^3 based on the Sabine's Reverberation equation and the Hopkins-Stryker equation for finding sound levels in a room. The Hopkins-Stryker equation was derived based on the assumption of a diffuse sound field.

$$L = 10\log\left[\frac{\rho c}{p^2_{ref}}\left(\frac{W}{4r^2}+\frac{4W}{A}\right)\right] \tag{4-3a}$$

where L is the total sound Level in dB, ρ is the density of air, c is the speed of sound in air, W is the sound power of the sound source in pW, r is the source to receiver distance, p_{ref} is the standard reference pressure of $2*10^{-5}$ N/m^2.

Overall Level (G) was derived from equation (4-1) and equation (4-3a) assuming that the sound source is omni directional. The term $\rho c/p^2_{ref}$ is treated as a constant.

$$G \text{ in dB} = 10 \log (100/r^2+31{,}200\ RT/V) \tag{4-3b}$$

The direct sound component can be ignored because "the prediction in total sound level beyond 20 m is only 0.3 dB" (Barron, 1988, p.621). Therefore, equation (4-3b) becomes

$$G \text{ in dB} = 10 \log (31{,}200\ RT/V) \tag{4-3}$$

The measured Reverberation Time (RT) in the equations was represented by measured Early Decay Time (EDT10) or Calculated Reverberation Time (RTs).

Barron and Gade found that Calculated Overall Level explained a large proportion of the variance of the hall averages of measured Overall Level.

Barron's Revised Theory for Concert Halls

A revised theory was proposed by Barron in 1973 to account for the variations of early sound energies among seats by dividing the received sound energy of the impulse response into three components:

1). the direct sound (D),

2). the early sound (delay < 80 ms, E_r) and

3). the late sound (delay > 80 ms, L) (Barron and Lee, 1988).

In addition to Reverberation Time (RT) in sec. and Room Volume (V) in m^3, the Distance to the Origin/Sound Source (r) in m was used to calculate the sound energy of the three components.

$$D = 100 / r^2 \tag{4-4}$$

$$E_r = (31{,}200\ RT/V)e^{-0.04\ r/RT}(1-e^{-1.11/RT}) \tag{4-5}$$

$$L = (31{,}200\ RT/V)\ e^{-0.04\ r/RT}e^{-1.11/RT} \tag{4-6}$$

Clarity Index (C80) and Overall level (G) can be derived based on the three components:

$$\text{C80 in dB} = 10 \log \left[(D + E_r) / L\right] \tag{4-7}$$

$$\text{G in dB} = 10 \log(D + E_r + L) \tag{4-8}$$

The measured Reverberation Time (RT) in the equations was represented by measured Early Decay Time (EDT10) or Calculated Reverberation Time (RTs).

Recent Studies Based on Acoustical Measurements Taken in A Large Number of Existing Halls

The method of using data gathered in a large number of halls to establish statistical relations among multiple acoustical measures or architectural parameters was initiated by Beranek in 1962. Several recent studies adopted this method and included many more acoustical measures or architectural parameters in the analyses.

Beranek

Beranek studied the audience seat absorption using both acoustical measures and architectural parameters measured in 51 concert halls. He concluded that "the absorbing power of a seated audience, chorus and orchestra increases in proportion to the floor area they occupied, nearly independently of the number of seated persons in that area" (Beranek, 1992, p.6). The architectural parameters Total Seating Area (Sa) and Seating Capacity (N) were developed for the current study.

Schroeder, Gottlob and Siebrasse

In 1979, Schroeder, Gottlob and Siebrasse studied the relations among several subjective preferences, acoustical measures and architectural parameters using a sample of 22 halls (Schroeder, Gottlob, and Siebrasse, 1979). Room Volume was positively correlated with Initial Time Delay Gap. Room Width was positively correlated with Early (0 ms to 50 ms) to Late Energy Ratio and negatively correlated with Reverberation Time. However, little new information regarding the effects of architectural parameters was derived because: 1) the emphasis of this study was given to the relation between the subjective preferences and the objective measures, and 2) Room Volume and Room Width were the only two architectural parameters used.

Barron and Lee

In late 1980's, methods for acoustical measurements in existing halls were greatly improved after digital signal processing techniques were developed. Several major studies were conducted that investigated the effects of architectural parameters on acoustical measurements taken in a large number of halls (Gade, 1991).

Barron and Lee presented a study in 1988 that compared acoustical measures with calculated estimates of the measures using equations 4-2, 4-3, 4-7 and 4-8

(Barron and Lee, 1988). They suggested that measured values of acoustical measures were correlated with the estimations based on their revised theory when certain architectural characteristics existed in the halls. They described these characteristics as

> "(a) a reasonably, but not excessively, diffusing ceiling; (b) some diffusion or breaking up of the side walls; (c) no substantial focusing, concave room surface; (d) no subdivision into independent spaces by balconies; (e) a reasonably proportionate space (i.e, height, width, and length are comparable); and (f) not a fan-shape plan with a wide splay. (Barron and Lee, p. 628)

Their analyses revealed that quantitative architectural parameters developed in halls with these architectural characteristics can be used to correct the estimations based on their revised theory. The architectural parameters associated with characteristics (a), (b), (d), (e), and (f) were developed for the current study. The parameters associated with diffusing surfaces (characteristics (a) and (b)) and balcony configuration (characteristics (d)) were not analyzed by other researchers that have conducted similar studies. These parameters were further discussed in a later section in this chapter.

Gade

From 1986 to 1991, a series of studies were presented by A.C. Gade based on a sample of 21 to 32 concert halls (Gade, 1989; Gade, 1990; Gade, 1991). He started rigorous analyses of relationships between hall averages of acoustical measures and architectural parameters by introducing more architectural parameters into successive studies.

Table 4-2. Architectural parameters used by Gade. Texts in the brackets are additional explanations of terms based on an interview with Dr. Gade.

Term	Definition
V	Volume
N	Number of Seats [including musician seats]
V/Sa	Volume per Seat
	Distance Between Seat Rows [seat back to seat back]
	Seat Width
Sa/N	Net Area per Seat
Lmax	Distance from Platform Front to Rearmost Seat
W	Mean Width Between Side Walls [at the main floor level]
H	Mean Ceiling Height
W/H	Mean Width / Mean Ceiling Height
WH	Mean Width × Mean Ceiling Height
L	Distance from Platform Front to Rearmost Seat / (Mean Width × Mean Ceiling Height)
2×Aw	Angle between Side Walls
Af	Floor Slope Angle [at the main floor level]

Table 4-2 summarizes the fourteen fundamental architectural parameters. The original terms were substituted by the similar terms developed in the current study. No further explanations of how they were measured were presented in Gade's publications. Parameters such as "Volume", "Seat Width", and "Distance from Platform Front to Rearmost Seat" are fairly straightforward . Some other parameters may be difficult to measure in actual rooms. For instance, "Width between Side Walls" may change from the main floor to the second balcony. In table 4-2, texts in the brackets are explanations of terms based on an interview with Dr. Gade in addition to the definitions presented by him.

The fourteen parameters included three interactions of some of the "raw" parameters that are directly measured or calculated from the drawings. The parameters associated with surface absorption were not used because the audience seating area in a concert hall normally represents the majority of surface absorption.

Figure 4-3. The significant correlations presented by Gade. '*' denotes the correlation between an acoustical measure and the logarithm of an architectural parameter.

	EDT10	C80	G	LEF
V	0.48		-0.82*	
W	0.57		-0.54*	-0.84
H			-0.66*	
Lmax			-0.67*	0.48
W×H	0.46		-0.73*	-0.83
W/H				-0.48
Lmax/(W×H)				0.52
Aw				-0.51
Af	-0.46	0.47		

Table 4-3 summarizes the significant correlations presented by Gade. The most significant correlation was found between architectural parameter W (Mean Width) and acoustical measure Lateral Energy Fraction (LEF). Another significant correlation was found between architectural parameter log(V) (logarithm of Volume) and acoustical measure Overall Level (G).

Table 4-4. The regression models of the acoustical measures presented by Gade.

Acoustical Measure	Regression Model	Model R Square in %	STD of Residuals
Early Decay Time (EDT10)	-0.16 + 1.08 × RT	95%	0.1 sec.
Clarity Index (C80)	-0.4 + 1.0 × C80_rt	64 %	1.0 dB
	-1.6 + 1.1 × C80_rt + 0.052 × W	71 %	0.9 dB
	-2.0 + 0.9 × C80_rt + 0.5 × W/H + 0.04 × Af	77 %	0.8 dB
	-1.6 + 1.1 × C80_rt + 0.5 × W/H + 0.013 × 2Aw	76 %	0.8 dB
Overall Level (G)	-1.6 + 0.90 × G_rt	87 %	0.9 dB
	-1.7 + 1.0 × G_rt - 7.4 × Lmax/(H×W)	88 %	0.8 dB
Lateral Energy Fraction (LEF)	0.41 - 0.0070 × W	53%	0.06
	0.28 - 0.0070 × 2Aw	26%	0.07

He also used estimations calculated using equations (4-2) and (4-3) and the architectural parameters to explain the variance of the acoustical measures. The variance of Early Decay Time (EDT10) and Overall Level (G) were well explained. Table 4-4 summarizes the regression models of the acoustical measures presented by Gade.

Most of the fourteen parameters used by Gade were developed for the current study. The parameters Seat Width and Distance Between Seat Rows were not adopted because they were not measured in some of the halls. Room architectural parameters such as Average Stage Width (Ws) were also developed to define the linear dimensions of the stage enclosure in addition to those defining the audience chamber enclosure.

Bradley

In 1989, an analysis of acoustical measures taken in 10 concert halls was presented by Bradley (Bradley, 1989). He suggested, qualitatively, that the shape of the ceiling determines the hall standard deviations of acoustical measures Early Decay Time (EDT10) and Overall Level (G). The high correlation between the Room Width (W) and the hall averages of Lateral Energy Fraction (LEF) that was previously suggested by Gade was not found in Bradley's study.

The architectural parameters associated with the shape of ceiling, such as Hs/H and Asc, were developed in this study in corresponding to Bradley's suggestion.

Hook

In the same year, a portion of a Master's thesis by J. Hook investigated the relationships among receiver specific acoustical measures and receiver architectural parameters in a concert hall (Hook, 1989). Acoustical measurements were taken at 52 receiver locations with a fixed sound source at the center front of the stage. A two dimensional coordinate system was constructed on the plan of the hall. The central axis of the hall was the main axis and the line crossing the sound source and perpendicular to the central axis was the orthogonal axis. Three receiver architectural parameters were derived from the coordinate system :

1. the distance from the receiver to the origin/sound source (r)
2. the distance to the main axis (y), and
3. the distance to the orthogonal axis (x).

Figure 4-1 represents the three architectural parameters with the terms that are similar to the ones developed for the current study.

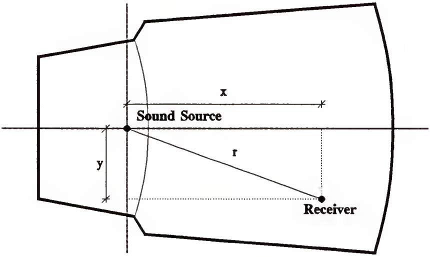

Figure 4-1. The three receiver architectural parameters used by Hook.

Table 4-5 summarizes the correlation coefficients among the acoustical measures and the receiver architectural parameters used in Hook's study. The coefficients in bold face are significant at the 95 % level. The acoustical measures Overall level (G), Clarity Index (C80), and Initial Time Delay Gap (t) all decrease as receiver architectural parameter r (or log(r)) increases. The acoustical measure Early Inter-aural Cross Correlation (IACC80) decreases as receiver architectural parameter y increases. However, it is a question whether the relations can be applied to other halls.

Table 4-5. Correlation Coefficients among the acoustical measures and the receiver architectural parameters presented by Hook.

	G	C80	t_I[1]	IACC80
x	**-0.97**	**-0.62**	**-0.56**	+0.10
y	-0.09	-0.25	**-0.46**	**-0.60**
r	**-0.97**	**-0.63**	**-0.61**	+0.06
log (r)	**-0.97**	**-0.74**	**-0.63**	+0.02

The coordinate system used by Hook was adopted in the current study. The vertical coordinate z was added as the third coordinate.

Others

Architectural parameters that were acoustically important but were not used by Gade, Barron, Hook, or Bradley were developed based on two types of sources.

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[1]. t_I denotes Initial Time Delay Gap that measures the time difference between the arrival of the direct sound form the stage and the arrival of the first strong reflection. This acoustical measures was not selected in this study because it is hard to apply the definition of this measure and obtain the expected results when the impulse responses measured digitally.

1. Specific effects of building elements analyzed by using acoustical measurements taken in full-size halls or scale models. The acoustical measures used in many of these studies were not the ones used in the current study. For example, the sound energy integrated from the direct sound over the first 40 ms (G_{40}) was used by Bradley to examine the seat dip effect (Bradley, 1991). Some of the studies were focused on a single building element instead of the entire hall. For example, the diffusing panels analyzed by Walsh involved just one panel (Walsh, 1979).
2. Many of the design principles that acoustical consultants have proposed based on their own approach of acoustics design of rooms.

Balcony Configurations

The importance of balcony configurations have been addressed in many of the text books on architectural acoustics since Beranek suggested that Under-Balcony Depth should be no greater than the Under-Balcony Height in a concert hall. A relatively deep balcony would cause "sound shadows" to the seats under the balcony because the paths of early reflections from the ceiling were blocked by the balcony floor. Ceilings under the balcony have been tilted to create paths of early reflections to the seats under balconies (Egan, 1988).

However, how much these parameters influence the selected acoustical measures has not yet been studied. Therefore, architectural parameters Under-balcony Depth (Dub), Under-balcony Height (Hub), Dub/Hub, and Under-balcony Ceiling Angle (Aub) were included in the current study.

Cremer also indicated that a coupled room effect exists at seats under or over deep and low balconies because the hall was partially divided. The reverberation time measured at these seats would be shorter than those measured at the seats on the main floor because the ratio of the area of absorbent surface (seats) relative to the volume in the space under or over the balcony was larger than those in the major hall space.

Over-balcony Depth (Dob), (Dob+Dub)/2, Hub/H, and Dub/Lmax were also used to describe how the hall was sub-divided, which Barron and Lee suggested was a critical condition for their revised theory. Figure 4-2 illustrates conceptually how the subdivision of a hall by balconies is measured by the proposed parameters and how "sound shadows"occur.

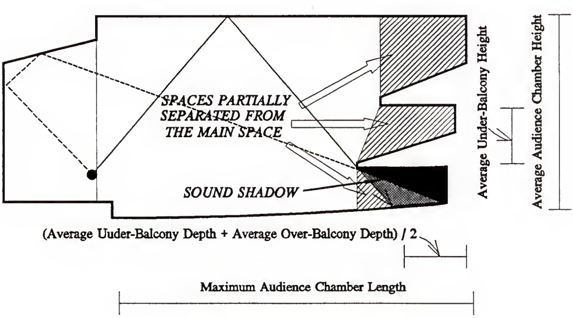

SPACES PARTIALLY
SEPARATED FROM
THE MAIN SPACE
SOUND SHADOW
Average Under-Balcony Height
Average Audience Chamber Height
(Average Uuder-Balcony Depth + Average Over-Balcony Depth) / 2
Maximum Audience Chamber Length

Figure 4-2. Illustrates showing conceptually how the subdivision of hall by balconies are measured by the proposed parameters and how "sound shadows"occur.

Furthermore, through a series of hall designs, some acoustical consultants have recently suggested that the existence of side boxes (or called tiers) would enhance second order early, lateral reflections to seats on the main floor (Cremer, 1988; Johnson, 1990). A qualitative parameter Side Box Design was developed to describe this feature with 0 representing "no side boxes" and 1 representing "with side boxes".

Overhead sound-reflecting panels

In 1941, the earliest example of modern overhead sound-reflecting panels was built over the stage of the London's Royal Albert Hall. From 1950 to 1959, many other halls were built with overhead panels. The overhead panels generally became the principle surfaces that create early reflections in a wide fan shaped hall.

In the current study, Average Stage Height (Hs) was used to define the height of the overhead panels and Average Stage Roof Height (Hsr) was used to define the height of ceiling above the overhead panels where the spaces between the two layers of ceiling was open to the audience chamber. Parameter Hs is equal to Hsr when only one layer of ceiling exists. The measurements of the two parameters were discussed later in a following section.

A study by Watters showed that low frequency sound reflected by curved or zig-zag overhead panels was attenuated when the panels were stepped rather than lined-up. Several recent studies based computer modelling also suggested that a canopy composed of many non-planar panels not only supplies early reflections but also provides diffusing sounds laterally to the listeners (Nakajima, Ando and Fujita, 1992). However, architectural parameters were not developed to describe both architectural characteristics because only three halls surveyed had suspended overhead panels with significant opening areas among the panels.

Diffusing Surfaces

Diffusing surfaces are the surfaces that "break up" or scatter sound waves that strike these surfaces from a specific direction are reflected in several directions, in a "diffuse" manner. Several design principles stated in the book by Knudsen and Harris regarding sound diffusion are still used as design guidelines today (Knudsen and Harris, 1958).

1. Diffusion not only increases the uniformity of the spatial distribution of sound pressure but also increases the uniformity in the rate of growth and decay of sound in a hall.
2. Diffusing surfaces are most effective when their size is the same order of magnitude as the wave length of sound. For periodic corrugated surfaces, the depth and the length of the undulation are the two major factors that determine the frequency dependency.

Figure 4-3 illustrates how the reflections from a zig-zag wall are dependent on wave-length relative to the wall panel size. The dependency was described by Cremer that "The wall reflects at low frequencies like a large flat mirror, at middle frequencies it generates more or less diffuse reflections, and at high frequencies it will behave like a series of small perfect mirrors inclined to one another" (Cremer, 1982, p.18).

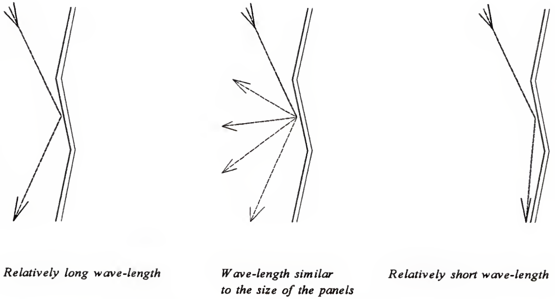

Relatively long wave-length
Wave-length similar to the size of the panels
Relatively short wave-length

Figure 4-3. Sketch illustrating how the reflections from a zig-zag wall are dependent on wave-length relative to the wall panel size.

3. Diffusion increases with increasing randomness of applied absorbent material.

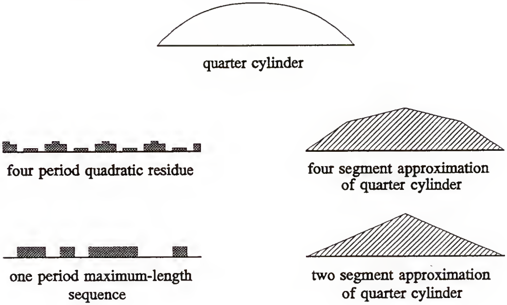
Architectural parameters were developed in the current study to measures design features corresponding to these principles.

1. Architectural parameters associated with the percentage of diffusing surface area to total surface area were developed to represented the amount of diffusing surfaces in a hall. They included Percentage of Diffusing Ceiling Surface, Longitudinal Direction (Pcdl), Percentage of Diffusing Ceiling Surface, Transverse Direction (Pcdt), and Percentage of Diffusing Wall Surface, Horizontal Direction (Pwd). These parameters were expected to be correlated with the hall standard deviations of acoustical measures.

2. The depth and the length of surface undulation were measured. The ceiling surfaces were measured longitudinally and transversely. The wall surfaces were measured only horizontally because the wall surfaces in many halls were divided vertically by side boxes.
3. No parameters were developed regarding the randomness of absorbent surfaces because the absorbent surfaces other than seats were generally concentrated in the lecture halls. There were only a few sound absorbent surfaces in the concert halls other than seating and small areas of carpet. .

Convex curved surfaces, pyramids, zig-zag surfaces, and plaster decorations in historical buildings are common types of diffusive surfaces. Binary maximum-length sequence (or pseudo-random sequence) surfaces were developed by Schroeder in 1974 to diffuse sound with a broad frequency range (Schroeder, 1975). The binary maximum-length sequence surfaces consisting of successive wells, with equal length but unequal depth can be designed based upon various number-theoretical schemes such as quadratic residues.

In 1979, experimental works by P. Walsh compared the scattering characteristics of several different types of diffusing surfaces that were constructed with the same base panel size. He suggested that the quarter cylinder is the most diffusive surface among the various types of surfaces chosen by him. He also compared several simplified schemes of a quarter cylinder. He concluded that there is a significant difference between a two-segment scheme and a four-segment scheme at higher frequencies. Once the segment number is larger than four, the simplified scheme can reasonably approximate a quarter cylinder (Walsh, 1979). Figure 4-4 illustrates several of the panels tested by Walsh. The quarter cylinder was compared to different types of pseudo-random sequences (left) and different schemes of approximated quarter cylinders (right).



quarter cylinder

four period quadratic residue

four segment approximation of quarter cylinder

one period maximum-length sequence

two segment approximation of quarter cylinder

Figure 4-4. Several of the panels tested by Walsh where the quarter cylinder was compared to different types of pseudo-random sequences (left) and different schemes of approximated quarter cylinders (right).

The architectural parameters associated with these types of diffusing surfaces were not used in the analyses, although they were recorded qualitatively. This is because a large number of parameters may be required to accurately record these types of features. However, architectural parameters Maximum Panel Size of Audience Chamber Ceiling (Lmcd) and Maximum Panel Size of Audience Chamber Side Wall (Lmwd) were developed to measure the maximum plan size of each undulation to approximately differentiate convex-curved surfaces from coffers or pyramids or zig-zag surfaces.

Low frequency seat dip effect and related architectural parameters

The low frequency seat dip effect occurs when sounds are propagated over rows of seats at a near grazing angle. Before sounds reach a listener, they are attenuated by the seats in an un-occupied hall. This effect was first observed by Békesy and was first measured using impulse responses by Schultz and Watters in 1964.

In conventional halls, there is a loss of intensity of tones (dip) between 50 and 500 Hz. By measurements both in a scale model and full-size halls, Bradley suggested that the effect is predominately dependent on the vertical angle of incidence of the direct sound (Bradley, 1991). When the angle of incidence is small, the seat dip effect is also dependent on the height of the receiver position over the seat back and the density of seats. However, he found out that the presence of other early reflections, such as those from a low ceiling or hanging panels, can mitigate the seat dip effect on a entire impulse response.

Two parameters were developed based on the study by Bradley: Angle of Incidence (*a*) was measured for each receiver position and Sa/N (Total Seating Area / Seating Capacity) was measured for each hall. Another parameter a/H (Angle of Incidence / Average Audience Chamber Height) was also developed based on the suggestion that the seat dip effect may be mitigated by early reflections from the ceiling. The height of the receiver position over the seat back was not measured because this information was not well recorded in some halls.

Coupled Room Effect

The coupled room effect occurs when a hall is spatially divided into a number of smaller volumes with relatively small openings among these spaces. Cremer illustrated that "a typical case of coupled rooms occurs in opera houses" where the stage house and the audience chamber are partially divided by the proscenium wall (Cremer and Müller, 1982, p.282). The average absorption coefficient is relatively large in the audience chamber because of the large number of seats while the average absorption coefficient is relative small in the stage house because of the open-air scenes. The rate of sound decay in the audience chamber is initially high but decreases when reverberant sound energy coming from the stage house becomes relatively strong. The rate of sound decay in the stage house is steadily low and is hardly influenced by the audience chamber. The coupled room effect has been recently implemented in concert hall designs to enhance the long term reverberation without hindering the audible clarity by installing large reverberation chambers that consist of reflective enclosures as coupled spaces (Johnson and Essert, 1992).

No architectural parameters associated with reverberation chambers were developed for the current study. This is because the only one hall, the Detroit Hall (hall O4), was designed with a reverberation chamber above the suspended panels in the stage house. The coupled spaces in the Festival Hall (hall M1) were not used when the acoustical measurements were taken. However, the architectural parameters associated with the balcony configuration were also indicative of how a hall was partially divided.

Measurements of architectural parameters

Measurements of architectural parameters were taken manually from plan and section drawings of the halls, mostly at 1/8"=1'0"or 1/16"=1'0" scale, and were later entered into Lotus spreadsheets. Two forms were developed to record measurements: a simple form was designed for small size halls where no balconies exist and a complex form was used for large size halls including churches, multi-use halls and concert halls. Figure B-1 in Appendix B shows the complex form used for large size halls.

The Coordinate System

A three dimensional coordinate system was developed based on the one used by Hook (Hook, 1989). The origin of the coordinate system is the sound source located at the center front of the stage. The x axis is the longitudinal (central) axis of the room intersecting the origin. The y axis is the axis perpendicular to the x (central) axis on the plan. The z axis is the vertical axis.

Receiver Architectural Parameters

The three coordinates of the receiver locations were measured. The absolute values of the y coordinates were used because all of the halls surveyed are symmetrical about the longitudinal axis. Two angular parameters, Vertical Angle of the Receiver (av) and Horizontal angle of the Receiver (ah), were calculated based on the three coordinates. Figure 4-5 illustrated the coordinate system and receiver architectural parameters measured for a receiver location.

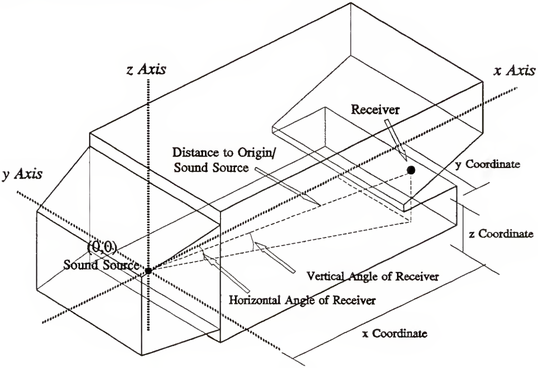


Figure 4-5. The coordinate system and receiver parameters measured for a receiver location.

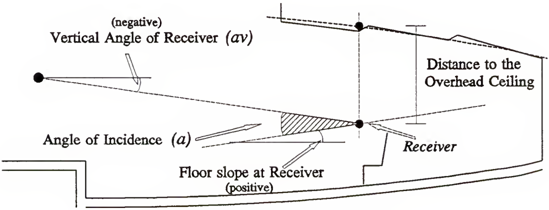


Figure 4-6. Receiver architectural parameters Distance to the Overhead Ceiling (rc) and Angle of Incidence (a).

Distance to the Overhead Ceiling (rc) was measured by the vertical distance from the receiver to the overhead ceiling. A smoothed line was used to approximate the ceiling on the drawing if the ceiling surface was rough. Angle of Incidence (a) was calculated by subtracting the Floor Slope at the receiver position from the vertical angle. Figure 4-6 illustrates how these two parameters were measured.

The angle of incidence was not measured at the position located at the side boxes if there were only one or two rows of seating in front of the receiver position. Parameter Distance to perimeter (rp) was used to measure the average distance to the perimeters which are sound normally reflective. It was calculated using several architectural parameters associated with average linear dimensions and receiver locations:

$$pr = \{[(L + Ls)/2 - |x - ((L - Ls)/2)|]^2 + (W/2 - |y|\,)^2 + rc^2\}^{1/2}$$

The parameters that define the relative location of the receiver in a hall were developed in addition to the ones that define the absolute locations. The architectural parameters used by Hook could represent the receiver location measured either way because only one hall was used.

Figure 4-7 illustrates a comparison of the absolute distance to the relative distance. Both receivers were located in the center of audience chamber of the two halls. The Distance to the Origin (r) relative to the Maximum Length of the Audience Chamber (Lmax) are the same while the absolute r value in the larger hall is twice as large as the r value in the smaller hall.

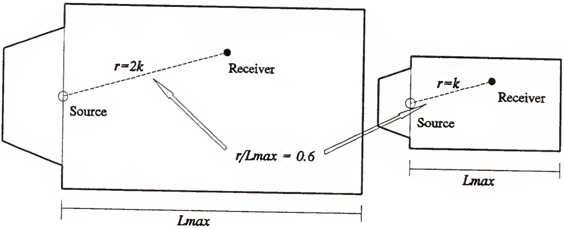


Figure 4-7. A comparison of the absolute distance to the relative distance in two halls.

Room Architectural Parameters

Room volume and seating capacity

Room Volume (V) was calculated manually based on the drawings. Details such as diffusing surfaces were approximated rather than calculated exactly. The coupled room volume at the stage in the Detroit Hall (hall O4) or at the side aisles in the Methodist Church (hall C1) was not included. Seating Capacity (N) included 70 seats on the stage in the concert halls and the multi-use halls used in concert mode and 40 seats in the churches.

Hall Enclosure

The hall enclosure was simplified before linear dimensions and angles were measured because 1) most of the major surfaces of the enclosure, especially in the large size halls, consisted of complex details, and 2) measurements in various halls would be consistent if the enclosures could be simplified to a similar configuration. A simplified enclosure consisted of a stage chamber and an audience chamber because there was distinctive change of hall height or hall width between the stage enclosure and the audience chamber enclosure in many of the large size halls.

The two chambers are primarily separated by the proscenium arch if it exists[2] or by the vertical plane defined by the y axis and z axis if there is no proscenium. Excluding the proscenium (or the y*z plane), each chamber is enclosed by a ceiling piece, two side wall pieces, a rear wall piece , and a floor piece. Figure 4-8 illustrates the simplified enclosure of a rectangular hall with one balcony.

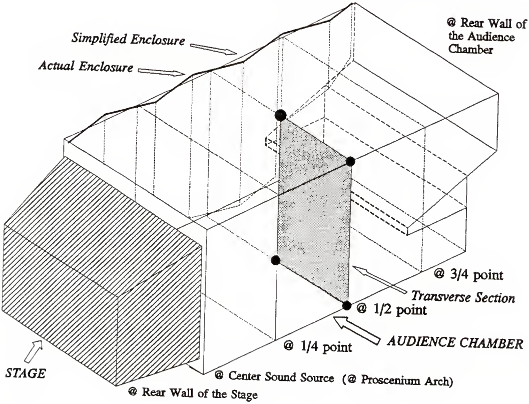


Figure 4-8. The simplified enclosure of a rectangular hall with one balcony and the transverse sections used to take measurements.

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[2] The center front sound source is approximately underneath the proscenium arch.

The back wall in the audience chamber that was the farthest from the origin was defined as the rear wall of the hall. If the side wall over the balcony and the side wall under the balcony were not lined up, the simplified enclosure of the audience chamber would consist of two side wall pieces.

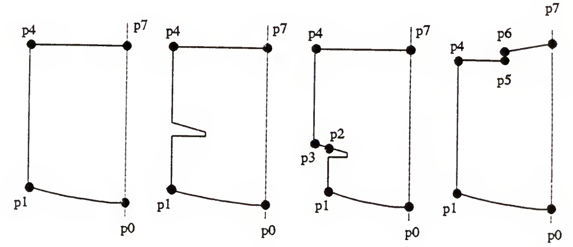
Measurements of coordinates of the simplified hall enclosure was based on seven transverse sections because all of the halls are symmetrical about the longitudinal axis and most of the halls have greater lengths than widths. As shown in Figure 4-8, the seven transverse sections were measured at

a. the rear wall of the stage,
b. the center sound source (or the proscenium arch),
c. the front wall of the audience chamber,
d. 1/4 point from source to the rear wall of the audience chamber,
e. 1/2 point from source to the rear wall of the audience chamber,
f. 3/4 point from source to the rear wall of the audience chamber, and
d. the rear wall of the audience chamber.

Section b and section c were the same in the halls where the side walls and ceiling continued smoothly from the stage to the audience chamber.

Coordinates of the key points on the seven transverse sections were measured. The key points were measured on only one side of the hall because all of the halls surveyed are symmetrical about the longitudinal axis.

Figure 4-9 represents sketches of key points on typical cases of transverse sections measured in the study where the numbering of the key points corresponded to the ones used in the data recording form shown in Appendix B. Points p0, p1, p4, and p7 were used to define a rectangle or a trapezoid. Points p2 and p3 were used if the side wall over the side box and the side wall under the side box were not lined up. Points p5 and p6 were used to describe additional details on the ceiling. No more than seven key points on a transverse sections were measured.



1.Flat ceiling
2.No side box

1.Flat ceiling
2.Side box with the same width over and below

1.Flat Ceiling
2.Side box with extended width over the box

1.Pitched Ceiling
2.No side box

Figure 4-9. Sketches of key points on typical cases of transverse sections of the halls investigated in the study.

Linear Dimensions. The average linear dimensions of the enclosure, such as Average Audience Chamber Width (W) and Average Stage Height (Hs), were calculated using the coordinates of the key points at the seven transverse sections. Among them, Average Audience Chamber Width was calculated using |y| of the key points at the main floor and |y| of the key points at the balcony floor if the width at the two floor levels was different.

Figure 4-10 shows a sketch of the simplified enclosure and the key points on the floor of a fan shape hall, Kleinhans Hall in Buffalo (hall O3). The vertical lines indicate the locations of the transverse sections. The coordinates of point *a* and point *b* defined the floor of the stage. The coordinates Point *c* to point *g* defined the main floor of the audience chamber. Point *g* was located at the place where the hatched area outside the rear wall approximately equals the blank area inside the corner of the rear wall. The process was used to improve the estimate of average audience width on the main floor since only five transverse sections were used. Point *h* was located at the place where the side and the rear wall intersect. The coordinate of point *h* point was used to calculate the side wall angle.

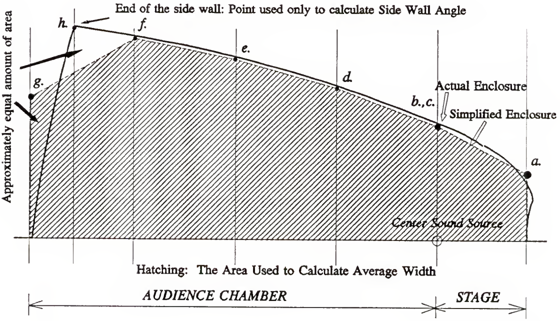

End of the side wall: Point used only to calculate Side Wall Angle
h.
f.
e.
d.
g.
b.,c.
Actual Enclosure
Simplified Enclosure
a.
Approximately equal amount of area
Center Sound Source
Hatching: The Area Used to Calculate Average Width
AUDIENCE CHAMBER
STAGE

Figure 4-10. The simplified enclosure and the key points on the floor of a fan shape hall, Kleinhans Hall in Buffalo (hall O3).

In the halls with overhead panels in addition to the ceiling and the spaces between the two layers of ceiling was open to the audience chamber, parameter Average Stage Height (Hs) was used to define the height of the overhead panels and Average Stage Roof Height (Hsr) was used to define the height of ceiling above the overhead panels. Figure 4-11 illustrates the overhead panels in the Festival Hall (hall M1). The overhead panels (defined by parameter Hs) were designed to create early reflections while the high ceiling (measured by parameter Hsr) provides the volume for long reverberation time.

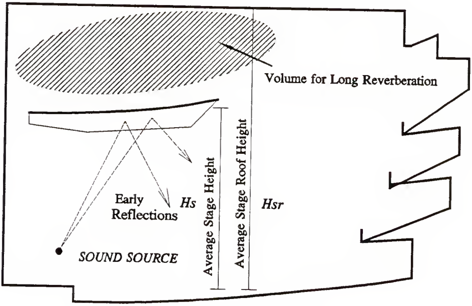


Figure 4-11. Illustration showing the overhead panels in the Festival Hall (hall M1).

Average Surface Angles. Parameters that described the overall slope of the ceiling and the side walls were also calculated based on the fit of a line to the coordinates of the key points defining the audience chamber side wall, stage side wall, audience chamber ceiling, and stage ceiling. The angle is positive when the splay of the side wall or the tilting of the ceiling is toward the rear of the audience chamber. The Average Audience Transverse Ceiling Angle (Act) was also measured at the transverse section located at the 1/2 point from the sound source to the rear wall of the audience chamber. A ceiling with a greater height at the center axis than at the side walls would have a positive angle.

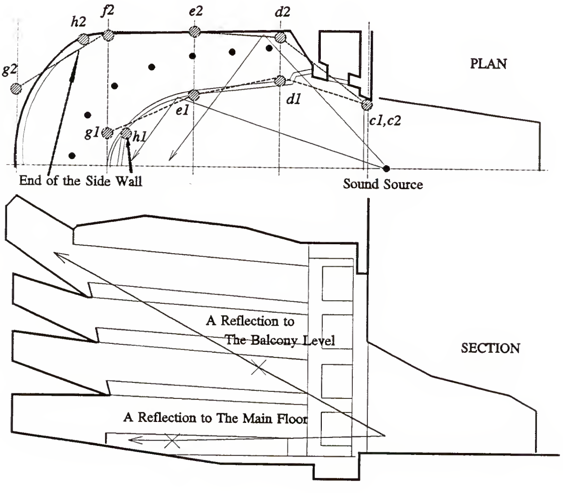


Figure 4-12. Sketches showing how the end of the side walls were defined and which wall was used as the side wall for the seats on the main floor in the Academy of Music in Philadelphia (hall O6).

The end of the side walls in a few halls was difficult to define because the side walls gradually faded into the rear wall. The end of the side walls in these halls was defined at the sides of the last row of seating. This was determined by the author because the walls behind the last row of seats can not effectively provide first order reflections unless the walls were canted towards the floor whereas the side walls were generally considered as the wall providing first and second lateral reflections to the audience (Barron, 1993). Figure 4-12 shows where the end of the side walls were defined and which wall was used as the side wall for the seats on the main floor in the Academy of Music in Philadelphia (hall O6). The wall surrounding the middle section of the main floor that was defined by points c1,d1, e1, f1, and h1 was considered as the side wall for the seats on the main floor because the wall provides first order lateral reflections to the main floor area. Point h1 defined the end of the side wall for the seats on the main floor and point h2 defined the end of the side wall for the seats on the balconies

Average surface panel Angle. The parameter "Angle between Side Walls" measured by Gade could mean the angle of the overall slope of the wall or the angle of the major panels. For instance, in reverse fan-shaped halls, the side wall panels are splayed facing the stage yet the overall shape of the plan may not be a reversed fan. Therefore, architectural parameters defining both types angles were developed. An average surface angles was calculated based on the fit of a line as stated previously. An average surface panel angle was calculated by adding the average surface angle with the angular difference between the major panels and the simplified enclosure of

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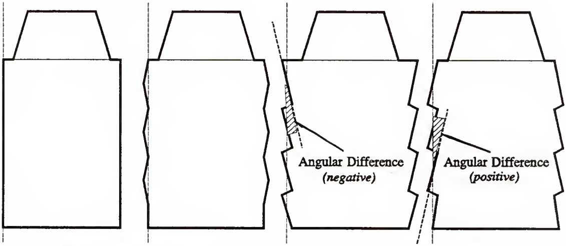


Side Wall Panel Angle (Awp) = Side Wall Angle (Aw) + Angular Difference

Hall A	*Hall B*	*Hall C*	*Hall D*
Aw = Awp	Aw = Awp	Aw > Awp	Aw < Awp

Figure 4-13. Sketch of three halls with the same Average Wall Angle of Audience Chamber (Aw) but different Average Wall Panel Angle of Audience (Awp).

Arrangements of Seats

How seats were arranged in a hall is important because the acoustical measurements were based on specific source-receiver paths. The arrangements of seats can be generally determined by the size and shape of the hall enclosure and balcony configuration because the floor areas in the audience chamber were generally filled with seats. However, it is easier to calculate the parameters associated with arrangements of seats, such as the average value of the Angle of Incidence, based the individual values of receiver architectural parameters instead of deriving these parameters from other room architectural parameters.

Therefore, most of the room architectural parameters associated with the arrangements of seats were calculated based on the average values and the standard deviations of the receiver architectural parameters measured at the selected receiver positions. The other parameters such as Sa/N (Total Seating Area / Seating Capacity) were calculated based on other "raw" room architectural parameters.

Balcony configuration

Architectural parameters associated with the balcony configuration were calculated based on coordinates of several key points at two sections of each level of balcony. The average values of linear dimensions of individual balconies were used if there were multiple balconies inside a hall. The sketch in figure 4-14 illustrates where the sections were defined in the Academy of Music in Philadelphia (hall O6). One section (section A) was taken along the longitudinal central axis of the hall and the parameters associated with the balconies were measured. The other section (section B) was taken along the edge of the side boxes and the parameters associated with the side boxes were measured.

Figure 4-15 represents the sketch of a balcony section with specified key points and the associated parameters. The key points were defined by the intersections of the line along the balcony steps, the line of the under-balcony ceiling, the line of the under-balcony rear wall and the line of the balcony rear wall.

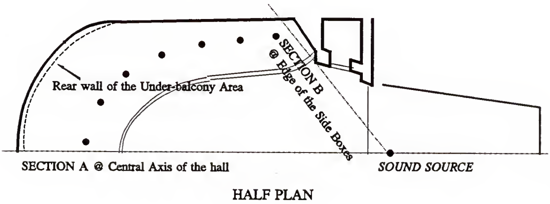

Rear wall of the Under-balcony Area
SECTION B @ Edge of the Side Boxes
SECTION A @ Central Axis of the hall
SOUND SOURCE
HALF PLAN

Figure 4-14. Sketches showing where the sections were taken in the Academy of Music in Philadelphia (hall O6).

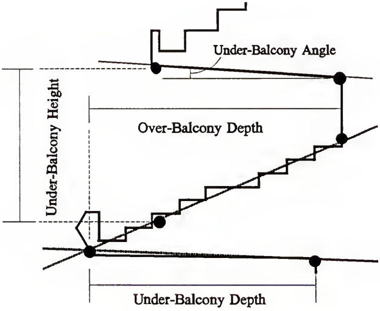


Figure 4-15. Sketch of a balcony section with specified key points and several associated architectural parameters.

Average Surface Absorption

Hall surfaces were measured and calculated according to information provided by architectural drawings, generally at a scale of 1/8"=1'0" scale. The surface area of the audience seats were calculated diagonally along the line linking the seat backs. while the surface area of the aisles included both the step depth and step rise if the floor consisted of steps rather than a slope. Figure 4-16 illustrates how the area of seats and area of aisles were calculated. The edges of audience seats were not included because a current method of including a 1 1/2 ft wide strip of seating area to account for the absorption of the edges was empirically derived. In the concert halls, the multi-use halls and churches, Total Seating Area (Sa) included the stage area because seats were on the stage floors of these halls when acoustical measurements were made.

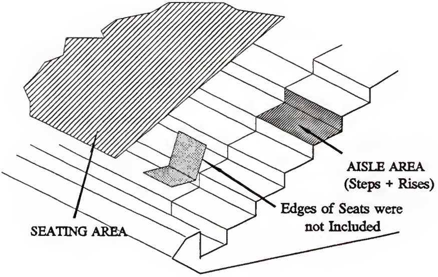


Figure 4-16. Illustration of how the area of seats and area of aisles were calculated.

Most absorption coefficient data were adopted from two text books on architectural acoustics (Doelle, 1973; Egan, 1988). The accuracy of absorption coefficient of seats is particularly important because seating areas generally represent the majority of the absorbent surfaces in music auditoria. However, only well accepted data were used because significant differences were found among recent studies.

Figure 4-17 represents a comparison of the generally used values for fabric well-upholstered seats presented by Beranek in 1969 with updated values presented by Beranek in 1993 (Beranek, 1993). The updated measurements by Beranek showed an increase of α at low frequency but decrease of α at the 1 kHz band. The data presented by Bradley in 1969 was used for fabric upholstered seats in this study regardless of the materials and shape of the seats because the data were well accepted. Figure 4-18 represents the range of α for five types of fabric upholstered seats presented by Bradley (Bradley, 1989). The range was particularly large in the 2 kHz and 4 kHz bands. However, the data presented by Bradley were not used in the present study because 1) the details of seats were not recorded during the site visits and 2) the values were apparently larger than the ones measured by Beranek in actual halls rather than in a reverberation chamber. Figure 4-19 is a plot of absorption coefficients of leather-covered upholstered seats comparing data presented by Egan to data presented by Doelle (Egan, 1988; Doelle, 1979). There was an approximately 0.2 difference over six frequency bands between the two sets of data. However, the data presented in Egan's book were used.

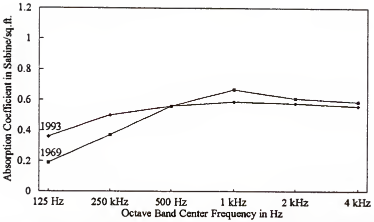


Figure 4-17. A comparison of the generally used values for fabric well-upholstered seats presented by Beranek in 1969 with updated values presented also by Beranek in 1993.

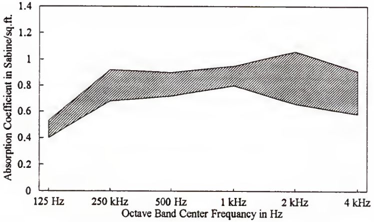


Figure 4-18. Five types of fabric upholstered seats presented by Bradley in 1989.

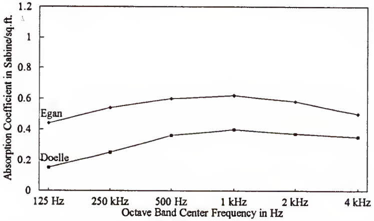


Figure 4-19. A plot of absorption coefficients leather-covered upholstered seats comparing the data presented in Egan' book to the data presented by Doelle' book.

Absorption coefficients of similar surfaces were used if no well-accepted data were available. For instance, the absorption coefficient of metal, plastic, or wood chair was used as acoustical coefficients for various types of unoccupied tablet-arm chairs in the lecture rooms. The absorption coefficients used for pipe organs were adopted from measurements made by Kinzey and Siebein where the average value over six frequency bands was approximately 0.3.

Bass Ratio based on Average Absorption Coefficient (BR(α)) and Treble Ratio based on Average Absorption Coefficient (TR(α)) were calculated as:

$$BR(\alpha) = (\alpha_{500\text{ Hz}} + \alpha_{1\text{ kHz}}) / (\alpha_{125\text{ Hz}} + \alpha_{250\text{ Hz}})$$

$$TR(\alpha) = (\alpha_{500\text{ Hz}} + \alpha_{1\text{ kHz}}) / (\alpha_{2\text{ kHz}} + \alpha_{4\text{ kHz}})$$

Diffusing Surfaces

The surface details related to sound scattering can be reasonably represented by details which are readable on the drawings with at scale of 1/8"=1'0" scale. This is because the sound frequencies of interest varied from the 125 Hz octave band to the 4 kHz octave band. The corresponding wave length of the center frequency of the six octave bands varied from 9 ft to 0.28 ft with the speed of sound equal to 1130 ft./sec. A distance of 0.3 ft is readable on the drawings at a scale of 1/8"=1'0". All the parameters associated with diffusing surfaces, except the ones related to the size of balconies, were calculated based on the longitudinal and transverse direction of the ceiling and the horizontal direction of the walls because the majority of the interior surface details of the hall in the sample were oriented in these three directions.

Any periodic corrugated surfaces were considered as diffusing surfaces if the depth was over 0.3 ft. This was measured relative to individual pieces of the hall enclosure no matter how large the absolute size of the pieces were or how long the length of the periodical undulations were. Figure 4-20 shows how the areas of ceiling diffusing surfaces were defined in the longitudinal section in the Severance hall (hall O). The ceiling surface in the front of the audience chamber was considered as flat as opposed to diffusing because the length of the flat surface is much larger than the length of the undulation of the periodical surfaces in the back of the audience chamber.

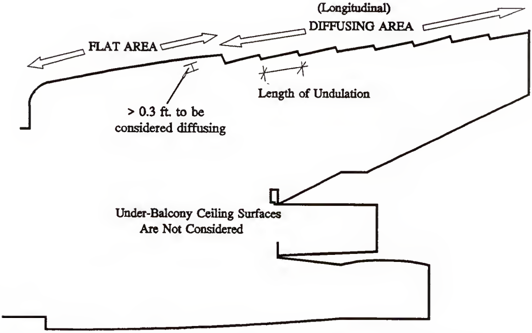
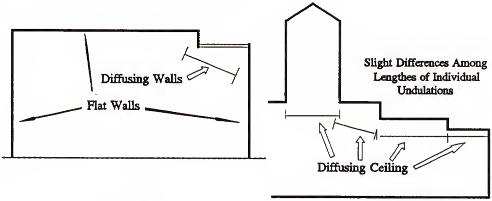

(Longitudinal)
DIFFUSING AREA
FLAT AREA
Length of Undulation
> 0.3 ft. to be considered diffusing
Under-Balcony Ceiling Surfaces Are Not Considered

Figure 4-20. Sketch showing how the ceiling diffusive surfaces were defined in the Severance Hall.

However, it is difficult to clearly distinguish the diffusing surfaces from flat surfaces in some halls when a) there is only one period of the corrugated surfaces or

b) the length of the undulations varied. Figure 4-21 shows how the diffusing on the side wall in Room 423 in Architectural Building in University of Florida (hall L3) (left) and on the ceiling of the Annie Pfeiffer Church (hall C2) (right) were defined. The small panels at the corner of hall L3 were defined as diffusing surfaces because they were very small relative to the length of the side wall and the length of the rear wall. All of the ceiling in hall C2 were considered as diffusing because the zig-zag continued from the central axis of the hall to the side wall while the changes of the length of each zig-zag did not change significantly. However, the depth of individual undulations significantly varied in hall C2.



HALL L3
HALF PLAN

HALL C2
TRANSVERSE SECTION

Figure 4-21. Illustration of how the diffusing on the side wall in Room 423 in Architectural Building in University of Florida (hall L3) (left) and on the ceiling of the Annie Pfeiffer Church (hall C2) (right) were defined.

Two types of room architectural parameters were measured after the diffusing surfaces were defined.

1. The percentage of the diffusing surface areas relative to the total surface area were calculated to account for the amount of diffusing surfaces.

2. The parameters associated with the depth, the length and the maximum panel size of the surface undulations were measured to account for the size of the diffusing surfaces. These parameters were measured regardless of the types of diffusing surfaces, i.e. whether the diffusing surfaces were zig-zag, coffered, or others shapes. The depth of the diffusing surfaces would be zero If there are no diffusing surfaces. Figure 4-22 shows how the depth, the length and the maximum panel size of the surface undulations were measured for two different types of diffusing surfaces.

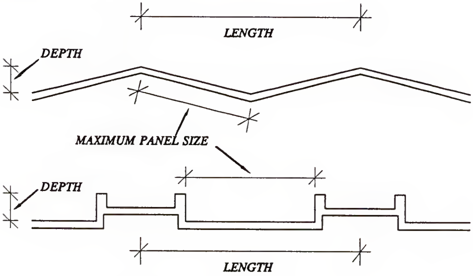


Figure 4-22. Sketch showing how the depth, the length and the maximum panel size of surface undulation were measured for two different types of diffusing surfaces.

4. The measurements of Average Side Box Depth (Dsb) and Average Side Box Height (Hsb) were stated previously. Side boxes were considered as diffusing surfaces because the depth of a side box generally varied from 4 ft to 12 ft. Therefore, the side boxes may diffuse low frequency sound vertically. However, details such as the size and orientation of balcony faces were not considered.

CHAPTER 5

STATISTICAL RELATIONS AMONG ROOM ARCHITECTURAL PARAMETERS AND THE HALL AVERAGES AND HALL STANDARD DEVIATIONS OF ACOUSTICAL MEASURES

The analyses in the following two chapters were conducted to quantitatively relate acoustical measures to architectural parameters and possibility interpret the relations. In this chapter, attention was given to the relations among the hall averages and hall standard deviations of acoustical measures and, respectively, the room architectural parameters. The hall averages and hall standard deviations of acoustical measures were calculated based on the acoustical measurements taken at multiple receiver locations in individual halls. The two sets of analyses presented in this chapter were conducted to examine the effects of architectural parameters beyond what can be explained by the diffuse sound field theory because the sound field of an actual hall is generally only partially diffuse.

The statistical relations were investigated by means of correlation analyses, factor analyses and multiple regression analyses. Factor analyses were used in conjunction with the analyses of correlation coefficients to identify groupings of architectural parameters because of the large number of room architectural parameters. Multiple linear regressions were conducted to study the combined effects of room architectural parameters on individual acoustical measures.

The relations among Room Architectural Parameters and Hall Averages of Acoustical Measures

This set of analyses was focused on the relations among room architectural parameters and hall averages of acoustical measures. The primary sources used to compare with the results included a) the calculated estimations using equations 4-1, 4-2, and 4-3, based on the diffuse sound field theory, b) the statistical relations previously presented by Barron and Gade, and c) design theories discussed in Chapter 4 such as the relation between parameter Angle of Incidence (A) and acoustical measure Bass Ratio Based on EDT (BR(EDT)).

Correlation Coefficients and Factor Analyses

Figure 5-1 represents the 95% significant correlation coefficients among room architectural parameters and spatial means of acoustical measures. Tables 5-1 to 5-5 summarize the rotated factor pattern for each acoustical measure. For each factor analysis, variables included the acoustical measure and the room parameters that were correlated with the acoustical measure at the 95 % significant level. Factor loadings presented are all significant at the 95 % level. The loadings of the acoustical measures are shown in boldface in the tables.

Early Decay Time (EDT10)

The rotated factor pattern for the hall averages of acoustical measures Early Decay Time (EDT10) and Clarity Index (C80) and the room architectural parameters that were significantly correlated with the two acoustical measures is summarized in Table 5-1. Three factors were found.

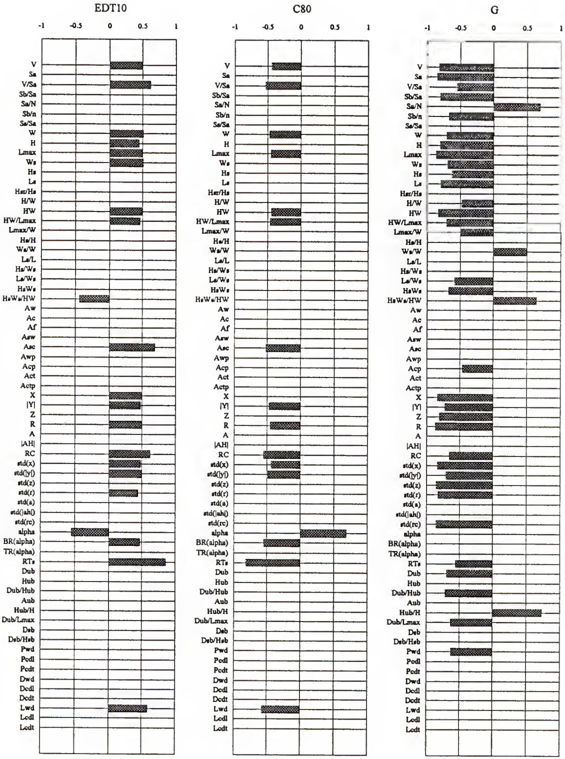


Figure 5-1. 95 % significant correlation coefficients among room architectural parameters and hall averages of acoustical measures.

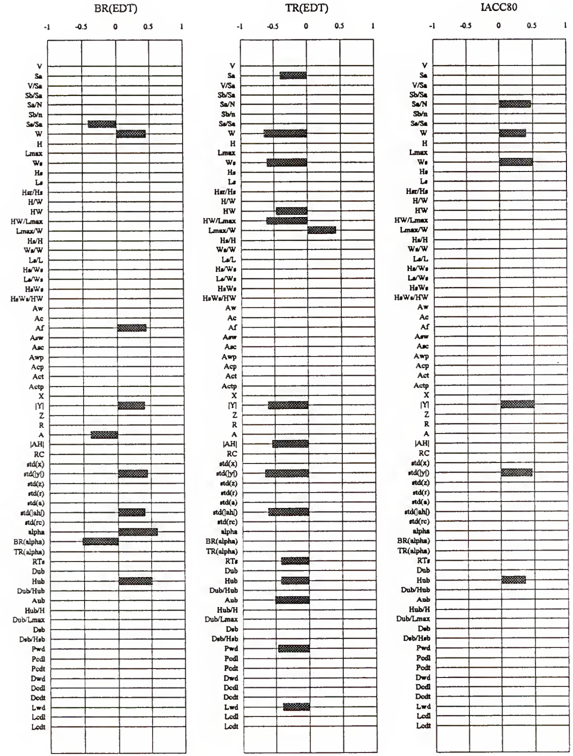


Figure 5-1. (Continued.)

1 Factor 1 can be defined as room size. The architectural parameter Average Distance to Overhead Ceiling (RC) has the strongest correlation coefficient ($r = 0.621$) among the room parameters that have significant loadings only on factor 1. The significant correlation between Room Volume (V) and Reverberation Time (RT) presented by Gade ($r = 0.48$) was also found in this study ($r = 0.487$) when RT was replaced by EDT10. The effect of Room Volume can be simply explained by equation (4-1), the Sabine's Reverberation Time equation. Room Volume, the numerator, changed by the power of three of linear dimensions when Surface Area× Surface Absorption, the denominator only changed by the power of two of linear dimensions.

2. Factor 2 can be defined as reverberation or surface absorption. The architectural parameter Average Absorption Coefficient (α) has the most significant correlation coefficient ($r = -0.547$) among the room architectural parameters that have significant loadings on only factor 2. Calculated Reverberation Time (RTs) has the strongest correlation coefficient ($r = 0.856$) among the room parameters that have significant loadings on both factor 1 and factor 2. The architectural parameter V/Sa (Room Volume / Total Seating Area) which is similar to the expression of the Sabine's Reverberation Time equation was also among this group. The correlation coefficient between EDT10 and V/Sa ($r = 0.618$) was less significant than the correlation coefficient between EDT10 and RTs. This can be attributed to the Total Seating Area (Sa) that did not accurately represent the absorbent surfaces in

these halls because much of the ceiling and wall surfaces were covered by absorbent panels in many of the lecture halls.

Table 5-1. The rotated factor pattern for the hall averages of acoustical measures Early Decay Time (EDT10) and Clarity Index (C80) and the room architectural parameters that were significantly correlated with the two acoustical measures.

	1 Room Size	2 Reverberation /Surface Absorption	3 Width
std(r)	0.933		
X	0.930		
std(x)	0.928		
Lmax	0.911		
R	0.909		
V	0.896		
H	0.876		
RC	0.853		
HW	0.839		0.494
V/Sa	0.755	0.415	
RTs	0.687	0.610	
HW/Lmax	0.603		0.590
HsWs/HW	-0.540		-0.463
Asc	0.453		0.422
C80		**-0.818**	
EDT10		**0.791**	
α		-0.746	
BR(α)		-0.744	
std(|y|)	0.426		0.896
|Y|	0.458		0.846
W	0.515		0.773
Ws	0.590		0.621
Asw		0.402	0.503
Percentage Variance	45.5	14.8	20.7

3. Most of the parameters that have significant loadings on factor 3 also have significant loadings on factor 1. They included the room architectural parameters associated with room width and the parameter Average Stage Ceiling Angle (Asc). The significant correlation (r= 0.507) between Room Width (W) and EDT10 agreed with the correlation (r=0.57) presented by Gade. The significant correlation coefficient (r=0.690) between room architectural

parameter Asc and EDT10 can be attributed to a tilted stage ceiling that projected more acoustical energy from the sound source to the audience area in many of the halls with longer EDT10's than a horizontal stage ceiling.

The significant correlation between EDT10 and Average Main Floor Slope (Af) presented by Gade (r = 0.45) was not found. The correlation coefficients between EDT10 and Af presented in the next chapter (Chapter 6) showed that the significant correlation can be found in the music halls but not in the lecture halls.

Clarity Index (C80)

The room architectural parameters that were significantly correlated with Clarity Index (C80) were similar to the parameters that were correlated with Early Decay Time (EDT10). This corresponded with the high correlation between these two acoustical measures (r = -0.932).

Overall Level (G)

A large portion of the room architectural parameters were significantly correlated with acoustical measure G. The rotated factor pattern is summarized in Table 5-2. Five common factors were found among the room architectural parameters that were significantly correlated with G.

1. Most room architectural parameters that have significant loadings on factor 1 also have significant loadings on factor 5. This is because the differences in room size represented by Factor 5 are the most prominent differences among all of the room architectural parameters. It is important to note that the rooms in the sample varied from a 54 seat lecture room to a 3,000 seat concert hall.

According to equation 4-3, G is expected to increase with an increase of the Calculated Reverberation Time (RTs) if V can be controlled. The positive correlation was not found in this study because of the significant changes of Room Volume (V) among halls. Yet, the regression model presented later in Table 5-8 showed a positive relation between RTs and the residuals of G that were not explained by parameter Room Volume (V).

2. Factor 2 can be defined as the y coordinates of seats or room width. The room architectural parameters Average Audience Chamber Width (W), Average of Absolute y Coordinates of Receivers (|Y|) and STD of Absolute y Coordinates of Receivers (std(|y|)) are all highly significantly correlated with G with $|r| \geq 0.7$. Many of the room architectural parameters that have significant loadings on factor 2 also have significant loadings on factor 5.
3. Factor 3 can be defined as the balcony depth. The room architectural parameter Average Under-balcony Depth (Dub) and Dub/Lmax (Average Under-Balcony Depth / Maximum Audience Chamber Length) were both significantly correlated with G with $|r| \geq 0.6$. Parameter Hub/H (Average Under-balcony Height / Average Audience Chamber Height) and Dub/Hub (Average Under-Balcony Depth/ Average Under-Balcony Height) were also significantly correlated with G when only the halls with balconies were used in the analysis. The negative correlation between G and Dub/Hub generally confirmed the effects of "sound shadows" caused by relatively deep balconies. The importance of this factor has been stated qualitatively in many books on

architectural acoustics, however, little quantitative information of this effect has been presented.

Table 5-2. The rotated factor pattern for the hall average of acoustical measure Overall Level (G) and the room architectural parameters that were significantly correlated with G.

	1 Reverberation	2 Width	3 Balcony Depth	4 Stage Width to Aud. Chamber Width Ratio	5 Room Size
V/Sa	0.798				
H/W	0.785				
Rc	0.739				0.502
H	0.687				0.626
HsWs/HW	-0.672	-0.422			
Sa/N	-0.566				
RTs	0.564				0.499
std(|ah|)		0.883			
std(|y|)		0.709		0.537	
|Y|		0.656			0.531
Lmax/W	0.561	-0.603			
HW/Lmax	0.494	0.532			0.524
Dub/Lmax			0.916		
Db			0.913		
Dub			0.870		
Sb/N			0.719		0.482
Sb/Sa	0.457		0.682		0.422
Actp			0.645		
std(z)	0.465		0.595		0.573
Z			0.511		0.591
Ws/W				-0.837	
LsWs	0.446			0.660	
Ls	0.485			0.559	0.478
HsWs					0.866
V	0.463				0.797
Sa					0.795
HW	0.471				0.763
std(x)	0.453				0.751
std(r)	0.420				0.736
R	0.483				0.722
X	0.499				0.717
Lmax	0.453				0.714
Ws		0.525			0.702
Hs					0.687
std(rc)	0.543		0.453		0.627
W		0.577		0.521	0.586
Pwd					0.535
G	**-0.455**		**-0.466**		**-0.525**
Percentage Variance	19.4	10.8	17.5	9.4	29.6

3. Factor 4 can be defined as stage width to audience chamber width ratio. The positive correlation (r = 0.491) between room architectural parameter Ws/W (Average Stage Width / Average Audience Chamber Width) and G showed the importance of the change of room width inside a hall. Hall average of G increased when the side walls were shaped to reflect sound towards the rear of the audience chamber.

5. Factor 5 can be defined as room size. The parameter Average Distance to the Origin/Source (R) has the most significant correlation coefficient (r = -0.872) among parameters that have significant loadings on factor 5. The parameters grouped by factor 5 also included Room Volume (V), Average Audience Chamber Width (W), Average Audience Chamber Height (H), HW, and Maximum Audience Chamber Length (Lmax) that were significantly correlated with G in Gade's studies (Gade, 1990).

Bass Ratio based on Early Decay Time (BR(EDT))

Only a small portion of room architectural parameters were significantly correlated with the hall average of acoustical measure Bass Ratio based on Early Decay Time (BR(EDT)). The factor analysis presented in Table 5-3 included acoustical measure BR(EDT) and the room architectural parameters that are correlated with BR(EDT) at the 91% significant level. The 91% significance level was used to include parameter Average of Angle of Incidence (*A*) in the analysis because parameter *A* has been suggested to influence the attenuation of the low frequency component of the direct sound in many publications (Bradley, 1991). Three factors were found.

1. Factor 1 can be defined as the average of absolute y coordinates of the receiver locations or room width. The correlation coefficients between BR(EDT) and the parameters grouped in factor 1 varied from $|r| = 0.4$ to $|r| = 0.45$. Why width but neither volume nor height was correlated with BR(EDT) is not clear at this point.
2. Factor 2 can be defined as surface absorption. As expected, the calculated Bass Ratio Based on Average Absorption Coefficient (BR_α) was correlated with BR(EDT) ($r = 0.52$). Room architectural parameter Average Absorption Coefficient (α) also had a significant loading on factor 2. Parameter $BR(\alpha)$ and parameter α were correlated because the sound absorbent panels that covered much of the wall and ceiling area in the lecture halls typically had lower absorption coefficients in the lower frequencies than they did in the higher frequencies.
3. The room architectural parameter Average Angle of Incidence (A) was only correlated with BR(EDT) ($r = -0.396$) at significance level of 91 %. Acoustical measure BR(EDT) increased as parameter "A" decreased because of the seat dip effect where the attenuation of direct sound and early side wall reflections at low frequencies increased as Angle of Incidence decreased. The low correlations between BR(EDT) and "A" agreed with the suggestion made by Bradley that the seat dip effect may not significantly influence the entire impulse response if there were strong early reflections from the ceiling (Bradley, 1991). However, parameter A was a unique variable among the

room parameters that were significantly correlated with BR(EDT) because it was the only parameter that had a significant loading on just factor 3.

Table 5-3. The rotated factor pattern of the hall average of Bass Ratio based on EDT10 (BR(EDT)) and the room parameters that are significantly correlated with BR(EDT).

	1 Width/ y Coordinates of Receiver	2 Surface Absorption	3 Std of Horz. Angle/Angle of Incidence
std($\lvert y \rvert$)	0.976		
$\lvert Y \rvert$	0.952		
W	0.934		
Af	0.451	-0.443	
Ss/Sa	-0.444		
α		-0.896	
BR_α		-0.733	
std(ah)	0.577		-0.748
BR(EDT)		**-0.691**	**-0.417**
A			0.645
Percentage Variance	36.0	21.2	13.3

The room architectural parameter Average Under-balcony Height (Hub) was significantly correlated with BR(EDT) in a reduced sample of only the halls with balconies ($r = 0.508$). This correlation was not further discussed because the parameter Hub is significantly correlated with Average Audience Chamber Width (W) which was one of the significant parameters included in factor 1.

Treble Ratio based on Early Decay Time (TR(EDT))

The rotated factor pattern for the hall average of Treble Ratio based on EDT (TR(EDT)) and the room parameters that were significantly correlated with TR(EDT) were summarized in Table 5-4. Only two factors were found.

1. Factor 1 can be defined as room size, reverberation time, or mean free path. The effect of room size, reverberation, or mean free path on TR(EDT) can be

attributed to the attenuation of high frequency sounds by air that increases as the path lengths of sound from the source to the receiver increased. The average path length of sound travel is related to the room size. The average paths of reverberant sound relative to the path of the direct sound is related to the reverberation time. The room architectural parameter STD of |y| Coordinates of Receivers (std(|y|)) has the strongest correlation coefficient (r = -0.649) among the room parameters that have significant loadings on factor 1. The inverse of room architectural parameter Room Volume (1/V) was correlated with TR(EDT) at the 95 % significant level (r = 0.501).

Table 5-4. The rotated factor pattern for the hall averages of acoustical measure Treble Ratio based on EDT10 (TR(EDT)) and the room architectural parameters that were significantly correlated with TR(EDT).

	1 Room Size/ Reverberation/ Mean Free Path	2 Width-Length Proportion
HW	0.989	
Sa	0.938	
HW/Lmax	0.855	
W	0.847	
Ws	0.838	
std(|y|)	0.831	-0.486
|Y|	0.829	-0.440
Pwd	0.759	
RTs	0.752	
Lwd	0.660	
AH		-0.962
std(|ah|)		-0.802
Lmax/W		0.795
TR(EDT)	**-0.504**	**0.577**
Percentage Variance	53.5	23.0

2. Factor 2 can be defined as the width-to-length proportion of the audience chamber. The negative correlation between the Standard Deviations of Horizontal Angle of Receivers (Std(|ah|)) and TR(EDT) (r = -0.609) showed

that the wider the hall, the lower the Treble Ratio. It is important to note that room width was smaller than the room length in 18 of the 22 halls. Whether this correlation can be applied to halls where the room width to room length ratio is much greater than 1 is not known at this point.

The room architectural parameter Treble Ratio Based on Absorption Coefficients (TR_α) was not correlated with acoustical measure TR(EDT) at the 95% significance level. Discussions regarding this issue are made in a later section.

Early Inter-aural Cross Correlation (IACC80)

The rotated factor pattern for the room architectural parameters that were significantly correlated with IACC80 were summarized in Table 5-5. Two factors were found.

1. The strong correlation between LEF and Average Audience Chamber Width (W) (r = -0.83) presented by Gade was not found in this study when IACC80 was used to replace LEF. Average Audience Chamber Width (W) was only correlated with IACC80 (r=0.398) at the 87% significant level in the current study. Two reasons may explain this: 1) Bradley found Room Width was better correlated with Early Lateral Energy than with Early Lateral Energy Fraction yet LEF is significantly correlated with IACC80 at mid frequencies (Bradley, 1989; Bradley, 1993) and 2) Gade suggested that LEF and W were better correlated in rectangular halls than in halls of other shapes (Gade 1990). Only three rectangular halls were surveyed in this study. However, other room architectural parameters that were associated with room width were

significantly correlated with IACC80. They all have significant loadings on factor 1. The parameter Average Absolute y Coordinates of the Receivers locations (|Y|) has the strongest correlation coefficient (r = -0.506) with IACC80 among these parameters.

2. Room parameter Sa/N (Total Seating Area/Seating Capacity) is the only parameter that has significant loading on factor 2. IACC80 generally increases with an increase of Sa/N. The effect of Sa/N was discussed in a following section because the correlation between Sa/N and IACC80 was strongly influenced by the IACC value of hall M1 where IACC80 were measured only at seats near the central axis.

Table 5-5. The rotated factor pattern for the hall average of acoustical measure Early Inter-aural Cross Correlation (IACC80) and the room architectural parameters that are significantly correlated with IACC80.

	1 Room Width	2 Seat Size
std(|y|)	0.998	
|Y|	0.939	
Ws	0.661	
IACC80	**0.436**	**0.770**
Sa/N		0.617
Percentage Variance	50.1	21.2

Calculated C80 and G Based on the Diffuse Field Theory

A specific task of this study was to examine how the calculated estimations of the acoustical measures based on equations (4-2) and (4-3) related to the measured values. Table 5-6 summarizes correlation coefficients between the measured hall average and the calculated values of acoustical measures C80 and G comparing the current results to Gade's findings. It is important to note that the measured Reverberation Time (RT) used in equations (4-2) and (4-3) was represented by the measured Early Decay Time (EDT10) or the Calculated Reverberation Time (RTs) in the current study.

Table 5-6. Correlation coefficients between the measured spatial means and the calculated values of acoustical measures C80 and G comparing the current results to Gade's findings.

		Calculated C80			Calculated G	
		(RTs)	(EDT10/RT)		(RTs)	(EDT10/RT)
Current	Measured C80	**0.867**	**0.968**	Measured G	**0.958**	**0.961**
Gade	Measured C80		**0.80**	Measured G		**0.93**

Table 5-7 summarized the regression models for acoustical measures C80 and G. The regressors include representative room architectural parameters for each factor and the corresponding estimations calculated using the two equations. A 95 % significance level was used as the variable entry criterion for the forward multiple regression procedure.

Table 5-7. The regression models for acoustical measures C80 and G.

Regression Models		R^2 in % total/partial	Std of Residual	Remarks
C80	-6.15 + 0.523×C80_rts + 2.29×log(V) + 2.54×1/AH - 22.6×log(RTs)	89 / 77	1.0 dB	
	0.38 + 0.981×C80_edt + 4.43×α	97 / 97	0.5 dB	
G	-0.427 + 0.875×G_rts - 1.25×Dub/Hub	88 / 76	1.0 dB	A
	-3.47 + 1.02×G_rts	92 / 92	1.6 dB	
	1.21 + 0.782×G_edt - 1.2×Dub/Hub	89 / 78	0.9 dB	A
	-1.47 + 0.88×G_edt	92 / 92	1.5 dB	

A. The sample including only halls with balconies

The correlation coefficient between the measured C80 and the Calculated C80 based on measured EDT10 (r = 0.968) is higher than the correlations presented by

Gade (r = 0.8). This may be because the measured Early Decay Time rather than the measured Reverberation Time was used to estimate C80 in this study.

Room architectural parameters were included in addition to the calculated estimations in many of the regression models. These parameters explained a significant amount of the variance that was not explained by the calculated estimations. These parameters can be considered as corrections to these equations.

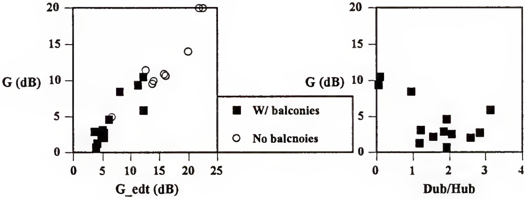


Figure 5-2. Scatter plots of Overall Level (G) as a function of Calculated Overall Level Using EDT10 (G_edt) (left) and G as a function of Dub/Hub (right).

Neither Calculated Overall Level Using EDT10 (G_edt) nor Calculated Overall Level Using RTs (G_rts) were good estimators for G when only the halls with balconies were included in the analysis. Yet, the models based on the subgroup of rooms were more accurate than those based on all of the rooms because additional architectural parameters were included. The scatter plots in figure 5-2 illustrated how Overall Level (G) is correlated with Calculated Overall Level Using EDT10 (G_edt) (left) and Dub/Hub (Average Under-Balcony Depth / Average Under-Balcony Height) (right). The inclusion of architectural parameter Dub/Hub reduced the standard deviation of residual to 0.7 dB. This is not a surprise because 1) the estimations were made based on the assumption of diffuse sound field and apparently a hall with relative deep balconies would not be a diffuse sound field because the hall was partially sub-divided 2) the direct sound component was removed from equation (4-3b).

The standard deviations of residuals for the models of C80 that varied from 0.5 dB to 1.0 dB was close to the 0.8 dB presented by Gade. The STD of residuals for the models of G was larger than the 1.0 dB presented by Gade except when only the halls with balconies were used in the regressions. This generally indicated an agreement among the two studies if the sample included only the music halls.

Sampling Bias for Early Inter-aural Cross Correlation (IACC80)

When binaural acoustical measurements were taken in the Methodist Church (hall C1) and Festival Hall (hall M1), the receivers were all located near the central axis. This only happened in these two halls because the acoustical measurements were made earlier in these halls than the measurements taken in most of the other halls. This was considered as a sampling bias because Hook suggested that IACC80 was significantly correlated with the y coordinate of the receiver.

Figure 5-3 represents a scatter plot of IACC80 as a function of room architectural parameter Sa/N (Total Seating Area / Seating Capacity). Each bubble indicates a hall. The notation of each hall corresponds to the label listed in Table 4-1. The size of each bubble indicates how much the Pearson correlation coefficient is influenced by the IACC80 values. Figure 5-3 shows that the correlation was strongly influenced by hall M1 because the hall average of IACC80 in hall M1 was the highest among all rooms.

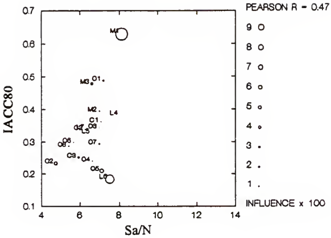


Figure 5-3. Scatter plot of IACC80 as a function of room parameter Sa/N where the notation of each hall corresponds to the label listed in Table 4-1.

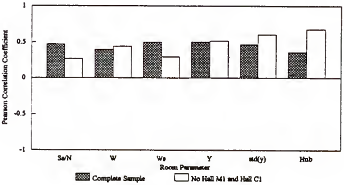


Figure 5-4. 95 % significant correlation coefficients among room architectural parameters and hall averages of IACC80 comparing the samples with and without halls M1 and C1.

Figure 5-4 represents the 95 % significant correlation coefficients among room architectural parameters and hall averages of IACC80 comparing the samples with and without halls M1 and C1. Several significant changes were found when halls M1 and C1 were removed from the sample.

1. The correlation coefficient between IACC80 and room architectural parameter Sa/N (Total Seating Area / Seating Capacity) decreased to 0.270.

2. The significance level of the correlation coefficient between IACC80 and room parameter Audience Chamber Width (W) was increased to the 95 % level (r = 0.440). However, this correlation coefficient was not as significant as Gade found (r = 0.80) probably because a) only three rectangular halls were used in the current study and b) LEF and IACC80 was not perfectly correlated. The correlation coefficient between the hall average of IACC80 and the hall average of LEF in the 500 Hz band presented by Bradley was approximately 0.8.
3. The correlation coefficient between IACC80 and room architectural parameter Under-Balcony Height (Hub) increased to 0.680. The hall average of IACC80 increased when low balcony ceilings blocked the strong reflections that arrived at the receivers from directions near the median plane of the receiver's head.

No significant correlation was found between Side Wall Panel Angle (Paw) and IACC80. This was examined because a small or negative Side Wall Panel Angle were suggested by Marshall to enhance early lateral reflections and decrease IACC80.

The Effects of Absorption Coefficients for Seats

The calculated value of Bass Ratio based on Average Absorption Coefficient (BR(α)) was generally higher than the measured Bass Ratio based on EDT10 (BR(EDT)) in this study although they were significantly correlated (r=0.520). The difference indicates that the absorption coefficients currently used for seating at low frequencies may be too small. This agrees with the recent measurements of seat absorption in halls taken by Beranek as shown in Figure 4-17.

The correlation between Treble Ratio based on Average Absorption Coefficient (TR(α)) and measured Treble Ratio based on EDT10 (TR(EDT) was poor ($r = 0.188$). The following statements may explain the poor correlation:

1. Air absorption was not accounted for in the average room absorption coefficient therefore the treble ratios in large halls were over-estimated.
2. The well-accepted values of absorption coefficient of upholstered seats did not provide enough discrimination among different types of seating actually found in the rooms. As shown in Figure 4-18, Bradley suggested that the differences among absorption coefficients for five types of seats were particularly significant at the high frequencies that would affect TR(EDT)..
3. The absorption coefficients of tablet-arm chairs used to calculate TR(α) may cause significant estimation errors because the absorption coefficients for metal, plastic, or wooden chairs were adopted.

A qualitative room architectural parameter, Seat Type (Kch), was used to distinguish the theater chairs from tablet-arm chairs. A value of 1 represented the tablet-arm chairs and a value of 0 represented the theater chairs. A significant correlation ($r = 0.489$) was found between this parameter and TR(EDT). When this parameter was multiplied by TR(α), the correlation coefficient between the parameter Kch× TR(α) and TR(EDT) was increased to 0.596. This indicated a significant difference of TR(EDT) between the two types of seats.

Regression Models

Multiple linear regression models were presented to study the combined effects of architectural parameters on individual acoustical measures. Selected architectural parameters that represented individual orthogonal factors were used as the regressors. Two criteria were used to examine the accuracy in the models, the Model R Square and the Standard Deviation (SAD) of residuals.

Table 5-8 summarizes the regression models for the hall averages of the six acoustical measures. The order of the variables listed in the models followed the order that the variable was entered in the Forward Selection procedures. The partial R^2 of the regressor that was entered first in the regression procedure (the one next to the intercept in the models presented in Table 5-8) is presented in addition to the total model R^2.

Table 5-8. Regression models for the hall average of the six acoustical measures.

Regression Models		R^2 in % total/partial	SAD of Residuals	Remarks
EDT	$1.874 + 0.897\times RTs - 0.383\times \log(V)$	81 / 73	0.23 sec	
C80	$3.75 + 34.6\times\alpha - 1.58\times\log(V) - 0.071\times Asc$	80 / 47	1.3 dB	
	$-5.47 - 15.0\times\log(RTs) + 1.96\times\log(V)$	85 / 76	1.1 dB	
	$-6.19 - 13.6\times RTs + 1.96\times\log(V) + 2.43\times 1/AH$	88 / 76	1.0 dB	
G	$58.7 - 9.7\times\log(V) + 0.116\times V/Sa - 0.935\times Dub/Hub - 280\times 1/W$	94 / 58	0.7 dB	A
	$64 - 12.9\times\log(V) + 0.176\times V/Sa + 0.283\times\lvert Y\rvert$	89 / 82	1.8 dB	
	$58.3 - 11.8\times\log(V) + 4.0\times RTs - 1.02\times Dub/Hub + 1.53\times Dub^{1/2}$	95 / 58	0.7 dB	A
	$57 - 11.0\times\log(V) + 4.13\times RTs$	92 / 82	1.5 dB	
BR	$0.705 + 0.123\times BR(\alpha) + 0.0019\times W - 0.0216\times A$	59 / 29	0.071	
	$0.543 + 0.258\times BR(\alpha) + 0.0022\times W$	56 / 41	0.045	A
TR	$1.05 - 0.112\times\log(\lvert AH\rvert) + 0.084\times Kch\times TR(\alpha) - 53.8\times 1/V$	58 / 45	0.035	
IACC	$0.063 + 0.00028\times\lvert Y\rvert^2 + 0.004\times(Sa/N)^2$	52 / 35	0.075	
	$0.053 + 0.0177\times\lvert Y\rvert + 0.108\times Hub/H$	55 / 37	0.057	B

A. Rooms with balcony only
B. Hall M1 and hall C1 removed

The number of architectural parameters contained in the models of acoustical measure Overall Level (G) was less than the number of factors shown in Table 5-2 because some of the parameters did not meet the 95 % significance level to enter the regression procedure. All of the regression models of G presented in Table 5-8 were as accurate as the models presented in Table 5-7 that contained the calculated estimations based on the diffuse sound field theory. This suggested that the hall average value of Overall Level (G) can be accurately estimated without using measured Early Decay Time (EDT10).

For acoustical measures EDT10, C80, and G, regression models with and without Calculated Reverberation Time (RTs) were both presented. The standard deviations of residuals and model R square of regression models were slightly improved when RTs was used in the models.

Regression models calculated based on a sub-group of the halls with balconies were also presented. Both criteria used to judge the regression models showed significant improvements when sub-groups of the sample were used. This indicated that the twenty two halls may be divided into at least two type of halls, the lecture halls and the music halls[1], to closely model the variance of acoustical measures. Sub-grouping of rooms was used in the analyses presented in the next chapter (Chapter 6).

The architectural parameter Calculated Reverberation Time (RTs) generally overestimated acoustical measure EDT10. This may be attributed to a) the edges of audience seats that were not accounted for to calculate room absorption and b) most of the surface absorptions were concentrated on the seating area on the floor but not on the ceilings and walls.

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[1]. The three churches were considered as music halls because their architectural characteristics were closer to concert halls than lecture halls.

The standard deviations of residuals were compared to the confidence intervals summarized in Table 3-3 to determine if it is worthwhile to derive more accurate models. The comparisons suggested no necessity to derive more accurate models because the standard deviations of residuals were generally as large as the 1/4 average confidence intervals.

The relations among Room Architectural Parameters and Hall standard deviation of Acoustical Measures

This set of analyses was focused on the relations among room architectural parameters and hall standard deviations (STD) of acoustical measures. Little information regarding such relations can be found in the literature. However, important room architectural parameters that were reviewed in Chapter 4 such as a) the shape of the ceiling (Bradley, 1989), b) the proportions of the room (Barron, 1988), c) balcony configuration (Beranek, 1962), and d) diffusing surfaces (Knudsen and Harris, 1958; Marshall, 1989) have been used as the sources to compare to the findings of the current analyses.

Correlation Coefficients and Factor Analyses

Figure 5-5 represents the 95% significant correlation coefficients among room architectural parameters and hall standard deviations of acoustical measures. Tables 5-9 to 5-14 summarize the rotated factor patterns for each acoustical measure. Factor loadings presented are significant at the 95 % level.

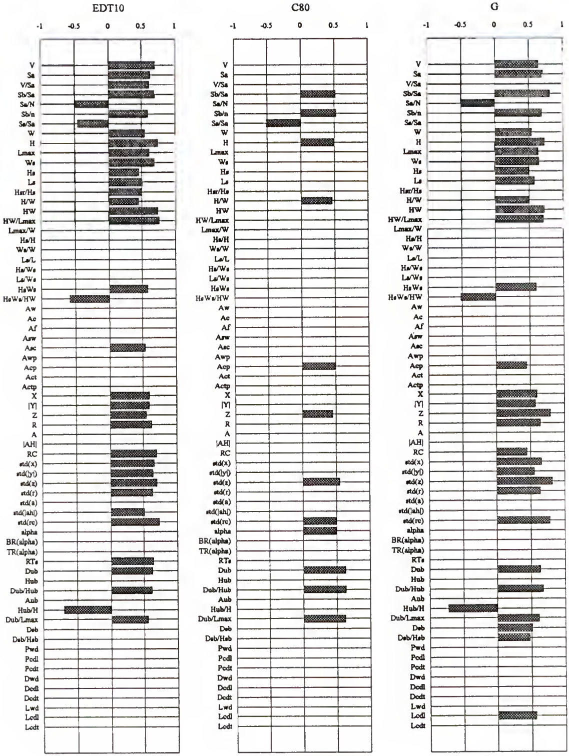

Figure 5-5. 95% significant correlation coefficients among room architectural parameters and hall standard deviations of acoustical measures.

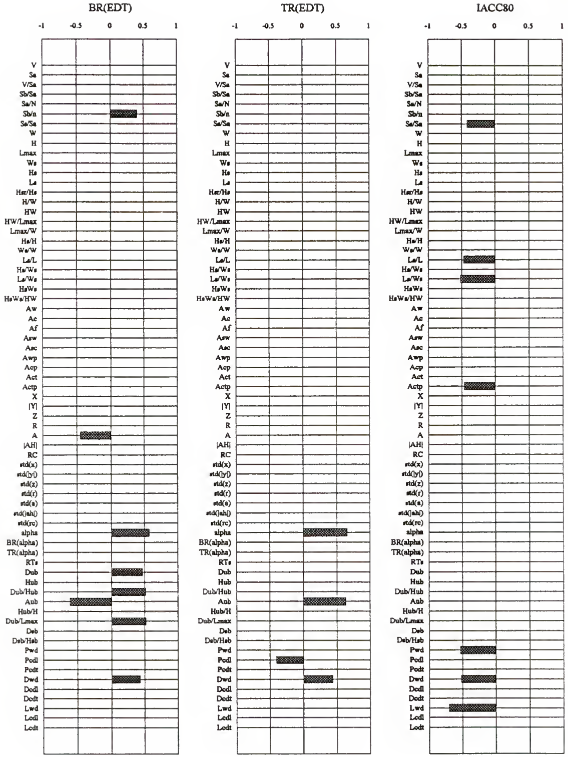

Figure 5-5. (Continued.)

Early Decay Time (EDT10).

A large portion of the room parameters were significantly correlated with the hall standard deviation of EDT10. Six common factors were found .

1. Factor 1 can be defined as balcony depth. The positive correlation between the room architectural parameters grouped by factor 1 and the hall standard deviation of EDT10 suggested that the more the hall was divided, the higher the variation of early decay time among seats was. The effect of balcony depth can be attributed to the effect of "sound shadows" underneath deep balconies and coupled room effects in exceptional cases.
2. Factor 2 can be defined as stage ceiling angle. The room architectural parameter Average Stage Ceiling Angle (Asc) was positively correlated with the hall standard deviation of EDT10 ($r = 0.539$). This agreed with Bradley's finding that the variation among seats increased when the ceiling was shaped to direct sound to the rear of the hall. The positive correlation between parameter Hsr/Hs (Average Stage Roof Height / Average Stage Height) and the hall standard deviation of EDT10 indicated that when sound reflective panels were suspended over the stage and the space over the panels was open to the audience chamber, the spatial standard deviation of EDT increased.
3. Factor 3 can be defined as the variation of horizontal angles of individual receiver locations. The larger the variation of horizontal angle was, the higher the variation of EDT was. The parameter Standard Deviation of Absolute Horizontal Angles of Receivers (std(|ah|) is normally large in a fan-shaped room

with wide splayed side walls or in a room where the seating areas of side boxes are large.

4. Factor 4 can be defined as room size, reverberation time, or mean free path. The room architectural parameter Room Volume (V) has the most significant correlation coefficient ($r=0.699$) among the parameters that had significant loading only on factor 3. Most of the room architectural parameters grouped by factor 4 were positively correlated with the hall standard deviation of EDT10 with $r > 0.7$.
5. Factor 5 can be defined as stage height to audience chamber height ratio. The room architectural parameter Hs/H (Average Stage Height / Average Audience Chamber Height) was negatively correlated with EDT10 ($r = -0.428$). This parameter was indicative of the overall ceiling slope including both the stage ceiling and audience chamber ceiling. This correlation may be attributed to the low stage ceiling that created early reflections to the seats near the stage. Early Decay Time (EDT10) was decreased by the early ceiling reflections at those seats and the variation of EDT10 among seats increased because EDT10 at the seats near the stage were generally shorter than EDT10 at the other seats in a hall.
6. Factor 6 can be defined as seat size in plan. The effect of this factor is not clear at this point.

No parameters that were associated with surface diffusion were correlated with the standard deviation of EDT at the 95 % significance level. This may explained by

Barron's suggestion that a flat ceiling covered with diffusing panels may not improve the distribution of sound because the reflections of a sound ray at oblique angles that occur at the rear of ceiling are relatively weak.

Table 5-9. The rotated factor pattern for the hall standard deviations of acoustical measure Early Decay time (EDT10) the room architectural parameters that were significantly correlated with the measure.

	1 Balcony-Depth	2 Stage Ceiling Angle	3 Variation of Horiz. Angle	4 Room Size/ Reverberation Time	5 Stage Height to Aud. Chamber Height Ratio	6 Seat Size
Db	0.936					
Dub/Lmax	0.913					
Dub	0.828			0.425		
Sb/Sa	0.689			0.579		
Sb/n	0.616	0.557				
Hsr/Hs		0.857				
V/Sa		0.725		0.512		0.452
H/W		0.584		0.487		
EDT		**0.536**				
HW/Lmax		0.528	0.496	0.505		
Asc		0.517				
std(|y|)			0.820	0.468		
std(|ah|)			0.781			
Y			0.769	0.529		
W			0.699	0.593		
Ss/Sa			-0.622			
Ws			0.587	0.530		
X				0.909		
Lmax				0.897		
std(r)				0.895		
R				0.891		
std(x)				0.884		
V				0.883		
Sa				0.872		
Ls				0.815		
HW				0.803		
std(rc)	0.445			0.768		
H		0.532		0.748		
std(z)	0.561			0.745		
z	0.449			0.735		
HsWs				0.685	-0.499	
RC		0.613		0.661		
Hs				0.649	-0.634	
RTs		0.465		0.596		
Hs/H					-0.782	
HsWs/HW					-0.594	
Sa/N						-0.503
Percentage Variance	15.05	12.41	13.81	38.39	4.97	4.08

Clarity Index (C80)

The number of room architectural parameters that were significantly correlated with the hall standard deviation of C80 were much less than the parameters that were significantly correlated with the hall standard deviation of EDT10 although Figure 3-3 indicated that the range of hall standard deviation relative to the overall standard deviation of C80 was larger than that of EDT10. Only three common factors were found.

1. Factor 1 can be defined as balcony depth. This factor is similar to the factor 1 for EDT10.
2. Factor 2 can be defined as room height. The relations between this factor and the standard deviations of C80 indicated that variation of C80 among seats increased with an increase of room height, either absolute height or height relative to width. It is interesting to find that other parameters associated with room size such as Room Volume were not correlated with the standard deviation of C80 at the 95 % level. This can be attributed to the halls with excessively high ceilings where only a small number of specular, early reflections can be created by walls. The small number of specular reflections arriving at the receiver located at the rear of the rooms can not compensate the attenuation of the direct sound due to the long source-to-receiver distance.
3. Factor 3 can be defined as surface absorption. The hall standard deviation of C80 increased with an increase of parameter Average Surface Absorption Coefficient (α). This is because early reflections were not evenly distributed

when much of the ceiling or walls were covered by absorbent panels and these absorbent panels were not evenly distributed on the hall surfaces. It is important to note that parameter α was not correlated with the hall standard deviation of EDT10 at the 95 % level.

Table 5-10. The rotated factor pattern for the hall standard deviations of acoustical measure Clarity Index (C80) and the room architectural parameters that were significantly correlated with the measure.

	1 Balcony Depth	2 Room Height/	3 Surface Absorption/ Stage Floor Area to Total Seating Are Ratio
Dub	0.887		
Db	0.879		
Dub/Lmax	0.860		
Sb/n	0.807		
Acp	0.691		
H		0.950	
std(rc)	0.436	0.859	
H/W		0.792	
std(z)	0.586	0.777	
Sb/Sa	0.649	0.701	
Z	0.516	0.678	
C80			**0.880**
α			0.529
Ss/Sa			-0.439
Percentage Variance	35.0	30.9	10.8

Overall Level (G)

Six common factors were found among the room architectural parameters that were significantly correlated with the hall standard deviation of acoustical measure G.

1. Factor 1 can be defined as room size. The parameters associated with the height have particularly significant correlation coefficients. Parameter std(rc) has the strongest (r=0.774) correlation coefficient among the parameters that

had significant loadings only on factor 1. The importance of room height has been found for acoustical measures EDT10 and C80.

Table 5-11. The rotated factor pattern for the hall standard deviations of acoustical measure Overall Level (G) and the room architectural parameters that were significantly correlated with the measure.

	1 Size	2 Balcony Depth	3 Variation of Horiz. Angle	4 Side Box Depth	5 Stage Cross Section to Aud. Chamber Cross Section Ratio / Seat Size	6 Height to Width Ratio
X	0.923					
Lmax	0.897					
R	0.896					
std(r)	0.892					
std(x)	0.877					
V	0.866					
Sa	0.827					
HW	0.802					
Ls	0.768					
RC	0.734					
H	0.716					0.507
HsWs	0.687					
std(rc)	0.674					
std(z)	0.656	0.537				
Z	0.627	0.463				
Hs	0.616					
Dub/Lmax		0.917				
Db		0.899				
Dub		0.884				
Sb/n	0.506	0.726				
Acp		0.693				
Sb/Sa	0.453	0.596				
G		**0.458**				
std(|ah|)			0.886			
std(|y|)	0.526		0.784			
|Y|	0.539		0.738			
W	0.663		0.665			
Ws	0.597		0.614			
HW/Lmax	0.514		0.610			
Dsb/Hsb				0.968		
Dsb				0.947		
HsWs/HW			-0.453		-0.653	
Sa/N					-0.450	
H/W					0.432	0.692
Percentage Variance	37.1	17.0	13.6	8.6	6.3	6.2

2. Factor 2 can be defined as balcony depth. The effect of this factor has been attributed to the effect of "sound shadows" underneath deep balconies where the paths of reflections from the stage ceiling and main ceiling of the audience chamber were blocked reducing the sound levels in these areas.
3. Factor 3 can be defined as the variation of horizontal angle. The effect of this factor has been discussed previously for acoustical measure EDT10.
4. Factor 4 can be defined as side box depth. The effect of this factor can be attributed to deep side boxes that created the paths of 2nd order or higher early reflections to the seats on the main floor but blocked the paths of early reflections to the seats on the balcony floor. This effect may be related to the balcony faces that were not accounted for in this study.
5. Factor 5 can be defined as two different architectural characteristics, stage cross section to audience-chamber cross section ratio and seat size. Parameter HsWs/HW (Average Stage Height × Average Stage Width / Average Audience Chamber Height × Average Audience Chamber Width) had a higher loading on factor 5. The hall standard deviation of G increased with a decrease of HsWs/HW. This may be because the front seats in the hall get strong early reflections when the height and width of the stage relative to the cross section of the audience chamber is small.
6. Factor 6 can be defined as height to width ratio. The positive correlation coefficient ($r = 0.489$) between parameter H/W (Average Audience Chamber Height / Average Audience Chamber Width) and the hall standard deviation of

G indicated that the variation of G among seats is large in a hall with a high ceiling. However, all of the values of H/W of the twenty halls are less than 1. It is questioned as to whether or not this correlation can be applied to a room with a H/W ratio larger than 1.

Bass Ratio Based on EDT (BR_EDT)

Two common factors were found among the room architectural parameters that were significantly correlated with the hall standard deviation of BR(EDT).

1. Factor 1 can be defined as balcony depth. The effect of factor 1 can be attributed to a coupled room effect. The reverberant energy coming from the major hall space to the space underneath a deep balcony was greater at low frequencies than at mid and high frequencies.
2. Factor 2 can be defined as surface absorption or the depth of wall diffusing surfaces. The correlation coefficient between the hall standard deviation of BR(EDT) and the Average Surface Absorption Coefficient (α) ($r=0.570$) is more significant than that between Depth of Wall Diffusing Surfaces, horizontal (Dwd) and the hall standard deviation of BR(EDT).

Both the Length of Diffusing Ceiling Surface, Longitudinal (Lcdl) and the Maximum Panel Size of Audience Chamber Ceiling, Longitudinal (Lmcd) were positively correlated with the hall standard deviation of BR(EDT). The two room architectural parameters were, however, significantly inter-correlated. The effect of parameter Maximum Panel Size of Audience chamber Ceiling (Lmcd) can be attributed to the diffusing surfaces with a maximum panel size larger than the wave-length (9 ft) of the center frequency of the lowest (125 Hz) band that did not effectively diffuse low frequency sound. The average values of Lmcd is over 11.87 ft as shown in Appendix C. The poor correlation between Maximum Panel Size of Audience Chamber walls (Lmwd) and the standard deviation of BR(EDT) is attributed to the values of Lmwd that are smaller than 9 ft in most rooms.

The parameter Average Angle of Incidence (*A*) was unique among all the parameters that were significantly correlated with the hall standard deviation of BR(EDT) because parameter *A* had no significant loading on either factor. The negative correlation (r = -0.450) between *A* and the hall standard deviation of BR(EDT) suggested that the variation of BR(EDT) among seats increases when seat dip effects were prominent.

Table 5-12. The rotated factor pattern for the hall standard deviations of acoustical measure Bass Ratio based on EDT10 (BR(EDT)) and the room architectural parameters that were significantly correlated with the measure.

	1 Balcony Depth	2 Absorption/ Side Wall Doff. Surface depth
Dub	0.994	
Dub/Lmax	0.954	
Db	0.948	
Sb/n	0.808	
BR(EDT)	**0.417**	**0.889**
α		0.650
Dwd		0.526
A		
Percentage Variance	46.1	19.8

Treble Ratio based on EDT (TR(EDT))

Only a few room parameters were significantly correlated with the hall standard deviation of TR(EDT) at the 95 % level. Two common factors were found among the parameters.

Table 5-13. The rotated factor pattern for the hall standard deviations of acoustical measure Treble Ratio based on EDT10 (TR(EDT)) and the room architectural parameters that were significantly correlated with the measure.

	1 Surface Absorption	2 Percentage Diff. Ceiling Surface
α	0.980	
TR(EDT)	**0.707**	
Dwd	0.440	
Pcdl		-0.822
Percentage Variance	41.5	23.8

1. Factor 1 can be defined as surface absorption. The effect of α on TR(EDT) was more significant than the effects of α on the other acoustical measures. This is because absorbent surfaces other than seats are generally the most absorbent in the 2 kHz and 4 kHz bands. The hall with the highest hall standard deviation of TR(EDT), hall L8, is also the only hall where the ceiling was totally covered by absorbent panels.

2. Room parameter Percentage of Ceiling Diffusing Surface in Longitudinal Direction (Pcdl) was the only parameter that has a significant loading on factor 2. The negative correlation between parameter Pcdl and the hall standard deviation of TR(EDT) ($r = -0.405$) simply suggests that a large amount of diffusing surfaces enhances distribution of high frequency sound. The

longitudinal surface of the ceiling is particularly important because the distance from the sound source to the rear wall of the audience chamber is generally much longer than the distance to the side walls.

The hall standard deviation of TR(EDT) was also positively correlated with the room architectural parameter Angle of Under-balcony Ceiling (Aub) (r = 0.631) based on data taken in the halls with balconies only. The reason for this relation is not clear at this point. However, the parameter Aub is negatively correlated with the hall standard deviation of BR(EDT) (r = -0.606). It is also interesting to note that the parameters associated with the depth or the height of balcony were not correlated with the STD of TR(EDT) at the 95 % significance level.

Early Inter-aural Cross Correlation (IACC80)

Many of the room architectural parameters associated with wall diffusing surfaces on the side walls were negatively correlated with the hall standard deviation of IACC80. Two common factors were found among all of the room architectural parameters that were significantly correlated with the hall standard deviation of IACC80.

1. Factor 1 can be defined as depth of wall diffusing surface or stage length. The parameter Depth of Diffusing Wall Surface in Horizontal Direction (Dwd) is correlated with the hall standard deviation of IACC80 (r = -0.518). The correlation can be attributed to the diffusing surfaces on side walls with reasonably large depth that effectively scatter sound at mid frequency horizontally. The hall standard deviation of IACC80 is also negatively

correlated with parameter Ls/Lmax (Stage Length / Maximum Audience Chamber Length) (r = -0.519) and Ls/Ws (Stage Length / Average Stage Width) (r = -0.469). These correlations indicated that the variation of IACC80 among seats increases with an increase of Stage Length.

2. The parameter Percentage of Diffusing Wall Surface (Pwd) is the only parameter that has a significant loading on factor 2. The relation between Pwd and the standard deviation of IACC80 (r = -0.529) is likely attributed to horizontal scattering of sound by walls with higher Pwd.

Table 5-14. The rotated factor pattern for the hall standard deviations of acoustical measure Early Inter-aural Cross Correlation (IACC80) and the room architectural parameters that were significantly correlated with the measure.

	1 Stage Length/ Depth of diff. Wall Surface	2 Percentage of Diff. Wall Surface
Acpt	0.820	
Ls/L	0.805	
Ls/Ws	0.745	
Dwd	0.726	
IACC80	**-0.549**	
Pwd		0.968
Percentage Variance	45.2	22.8

Regression Models

Multiple linear regression models were derived to study the combined effects of architectural parameters on individual acoustical measures. Selected architectural parameters that represent individual factors were used as the regressors. Table 5-15 summarizes the regression models for the hall standard deviations of the six acoustical measures.

Table 5-15. The regression models for the spatial standard deviation of the six acoustical measures.

Regression Models		R^2 in % total/partial	STD of Residuals	Remarks
EDT	$0.0152 + 0.0038\times\text{std(rc)} + 0.00072\times\text{Asc} + 0.024\times\text{Hsr/Hs}$	77 / 54	0.023 s	
	$-0.0117 + 0.0082\times\text{RTs} + 0.0062\times\text{std}(\lvert y\rvert) + 0.0168\times\text{Hsr/Hs}$	90 / 48	0.012 s	A
C80	$1.26 + 1.24\times\text{Dub/Lmax} - 0.106\times 1/\alpha$	54 / 40	0.27 dB	
	$1.14 + 0.704\times\text{Dub/Lmax} - 0.078\times 1/\alpha - 1.63\times\text{Ss/Sa} + 0.67\times\text{H/W}$	73 / 40	0.20 dB	
	$-0.048 + 0.288\times\text{Dub/Hub} + 0.012\times\text{H}$	64 / 47	0.24 dB	A
G	$1.38 -15.6\times 1/\text{R} + 1.42\times\text{Dub/Lmax} + 0.017\times\text{HW/Lmax} - 0.01\times\text{Dsb/Hsb}$	72 / 53	0.33 dB	
	$-0.395 + 0.124\times\text{std(z)} + 86.1\times 1/\text{R} - 3.04\times\text{Hub/H}$	90 / 50	0.16 dB	A
BR	$0.037 + 0.301\times\alpha - 0.104\times 1/\lvert\text{Y}\rvert - 0.0046\times A$	76 / 33	0.013	
	$-0.015 + 0.0132\times\text{Dub/Hub} + 0.247\times\alpha$	77 / 65	0.010	A,C
TR	$0.015 + 0.599\times\alpha^2 - 0.00018\times\text{Pcdl}$	67 / 56	0.013	
	$0.0033 + 0.0011\times\text{Aub} + 0.356\times\alpha^2$	53 / 40	0.008	A
IACC	$0.139 - 0.00047\times\text{Pwd} - 0.153\times 1/\lvert\text{AH}\rvert - 0.0058\times\text{Dwd}$	58 / 28	0.022	
	$0.127 - 0.000476\times\text{Pwd} - 0.0057\times\text{Dwd}$	45 / 32	0.023	D

A. Rooms with balcony only
B. Hall M1 and hall C1 removed
C. Rooms with diffusing ceiling surfaces only
D. Rooms with diffusing wall surfaces only

The room architectural parameters associated with a few major factors primarily explained much of the hall standard deviations of many of the acoustical measures.

1. The architectural parameters associated with room size or reverberation such as Room Volume (V) and Average Audience Chamber Height (H), the parameters associated with balcony configuration such as Dub/L (Average Under-balcony Depth / Maximum Audience Chamber Length) and the parameter Average Surface Absorption Coefficient (α) explained a major portion of the variance of the models for most of the monaural acoustical measures, i.e., all six measures except IACC80.

2. The parameters associated with the amount or the size of diffusing surfaces, such as Percentage of Diffusing Wall Surface (Pwd), explained a reasonable portion of the variance of acoustical measures TR(EDT) and IACC80.

Other minor factors were also identified. They primarily included the proportions of the hall enclosure represented by architectural parameters such as H/W (Average Audience Chamber Height /Average Audience Chamber Width) and the overall shape of the ceiling represented by parameters such as Hs/H (Average Stage Height / Average Audience Chamber Height).

Regression models calculated based on sub-groups of the sample were also presented. Significant improvements based upon the two criteria to assess the accuracy of the models were obtained when sub-groups of the sample were used.

The standard deviations of residuals of the regression models were compared to the average confidence interval of individual values of the hall standard deviations of acoustical measures summarized in Table 3-3. The comparison generally indicated that there is no need to obtain more accurate models for all of the acoustical measures because the range between confidence intervals of the hall standard deviations of acoustical measures are generally wide.

CHAPTER 6

STATISTICAL RELATIONS AMONG ARCHITECTURAL PARAMETERS AND ACOUSTICAL MEASURES AT INDIVIDUAL RECEIVER LOCATIONS

The objectives of this portion of study were a) to analyze the correlations among architectural parameters and acoustical measures at individual receiver locations, b) to combine room architectural parameters with receiver architectural parameters, and c) to compare the two sets of statistical relations derived for two set of rooms that are architecturally different. The study in this chapter is important because modern acoustical measurements of impulse responses are taken based on specific source to receiver paths.

A pilot study was conducted to analyze the correlations among receiver architectural parameters and acoustical measures at individual receiver locations in each of the eight concert halls. The results of this study were limited by the small number of receivers taken in some rooms because the magnitude of correlation coefficients had to be very high, especially for acoustical measure IACC80, to meet the selected significance level of 95 %. However, two conclusions can be drawn form this pilot study:

1. The correlations between receiver architectural parameters and acoustical

measures were similar among rooms for acoustical measures RT20[1], C80, and G.

2. the correlations changed by rooms for acoustical measures BR(RT), TR(RT) and IACC80.

The second conclusion suggested that the correlations between receiver architectural parameters and the three acoustical measures were dependent on the architectural characteristics of rooms. The dependency may be represented by the interactions between room architectural parameters and receiver architectural parameters.

Another pilot study was conducted to analyze the correlations among acoustical measures and the interaction parameters just mentioned. Some interaction parameters represented the relative positions such as r/R (Distance to the Origin/Source / Average Distance to the Origin/Source). The others, such as $r \times \alpha$ (Distance to the Origin/Source × Average Absorption Coefficient), were the interactions between receiver parameters and the major room architectural parameters that were significantly correlated with either the hall averages or the hall standard deviations of the acoustical measures. Seventeen interaction parameters were selected after the correlation coefficients were calculated between interaction parameters and room architectural parameters or between interaction parameters and receiver architectural parameters to examine if they were significantly inter-correlated.

All six acoustical measures except IACC80 were measured at a total of 156 receiver locations in the 22 rooms. IACC80 was measured at only 81 different receiver locations in 18 rooms. The complete sample was divided into two groups with one containing all the data in the music halls and the other containing all the data in the lecture halls. The rooms with balconies were contained in the subgroup of music halls. As stated previously in Chapters 4 and 5, the sub-grouping was made because

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[1]. Reverberation Time (RT20) rather than Early Decay Time (EDT10) was used in this pilot study.

1. there were apparent differences of architectural characteristics among the two types of rooms and
2. there were significant improvements of model R squares and standard deviations of residuals when only the rooms with balconies were used.

The relations among IACC80 and the architectural parameters of the lecture halls were not studied because IACC80 was measured in only four lecture halls.

Correlation Coefficients among Acoustical Measures and Room Architectural Parameters

The correlations among room architectural parameters and acoustical measures at individual receiver locations were studied to examine the changes of magnitude and significance of correlation coefficients when the acoustical measures were changed from hall average values to values measured at individual receiver locations.

Only selected room architectural parameters studied in Chapter 5 were used because many of the parameters were significantly inter-correlated according to the factor analyses. However, the parameters that were significantly correlated with either the hall averages or hall stand deviations of acoustical measures BR(EDT), TR(EDT), or IACC80 were all selected.

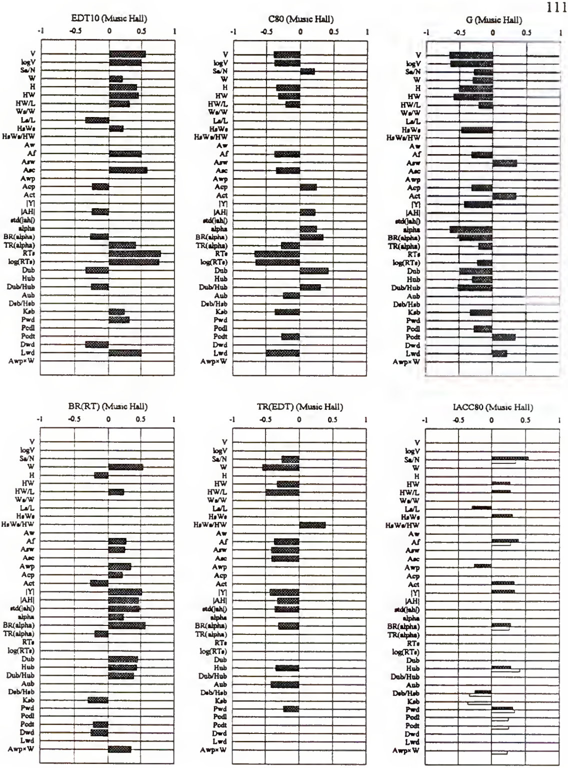


Figure 6-1. 98 % significant correlation coefficients among room architectural parameters and acoustical measures at individual receiver locations in all of the music halls (▩); in all of the music halls except hall M1 (☐).

Figure 6-1 represents the 98 % significant correlation coefficients among room architectural parameters and receiver specific acoustical measures in the music halls. The significance level used for the music halls (98 %) was slightly higher than the level used for the lecture halls (95 %) because that the total number of receiver locations in the music halls was much larger.

The room architectural parameters that were positively (negatively) correlated with Early Decay Time (EDT10) were generally negatively (positively) correlated with Clarity Index (C80). This agreed on of the findings stated in Chapter 5. The magnitude of the correlation coefficients among receiver specific values of Overall Level (G) and room architectural parameters was significantly smaller than the magnitude of correlation coefficients derived based on hall average values of G.

Several significant correlations were found in the music halls in addition to the correlations presented in Chapter 5 where the hall average values of acoustical measures were used.

A. Average Under-balcony Depth (Dub) was correlated with acoustical measures EDT10, C80 and G. The correlations suggested the decrease of reverberant energy caused by a deep balcony. This also suggested the increase of early energy created by shallow balconies because the distances to overhead ceiling were significantly reduced at the seats under or over the balconies.

B. Average Main Floor Slope (Af) was correlated with EDT10, C80 and G. These correlations agreed with Gade's findings.

C. Sa/N (Total Seating Area / Seating Capacity), Dsb/Hsb (Average Side Box Depth / Average Side Box Height), Side Box Design (Ksb), Awp×W (Average

Audience Chamber Side Wall Panel Angle × Average Audience Chamber Width) were correlated with acoustical measure IACC80. The correlation between parameter Ksb and acoustical measure IAAC80 (r=-0.353) agreed with a design theory that the existence of side boxes created second or higher order lateral reflections which decreased the Inter-aural Cross Correlation. The relation between parameter Awp×W (Average Audience Chamber Side Wall Panel Angle × Average Audience Chamber Width) and acoustical measure IACC80 (r = 0.236) agrees with another design principle that a reverse fan-shaped hall would enhance lateral refections. However, there were no reverse fan-shaped halls in the sample if hall M1 was excluded.

D. Average Ceiling Panel of Audience Chamber (Acp) were correlated with acoustical measures EDT10, C80, G and BR(EDT). A hall with the ceiling panels tilted towards the rear of the Audience Chamber, i.e, with a large Acp, would results in high C80 and low EDT10 because early reflections were direct to the seats at the rear of the audience chamber.

E. Room Architectural parameters associated with the depth of balcony were correlated with acoustical measures BR(EDT). The positive correlation between Dub/Hub (Average Under-Balcony Depth / Average Under-Balcony Height) and BR(EDT) (r = 0.396) can be attributed to the coupled room effect that the reverberant energy coming from the major hall space to the partially separated space under a deep balcony is greater at low frequencies than at mid and high frequencies.

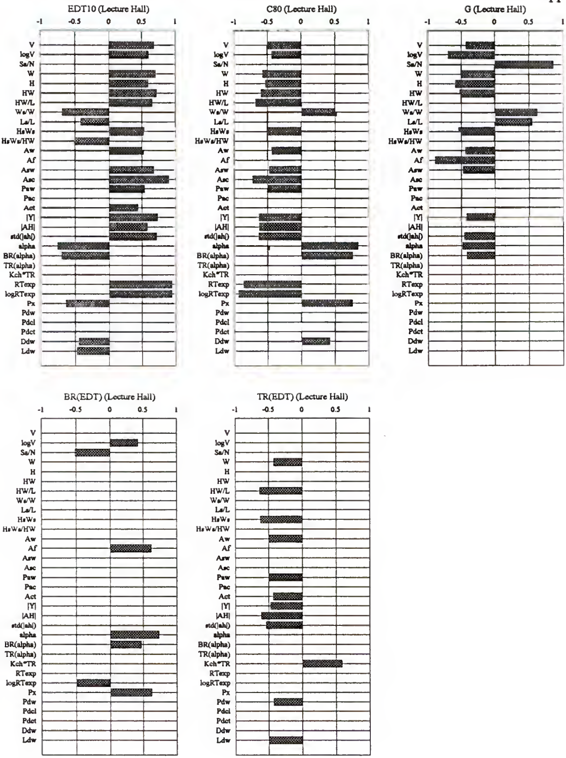


Figure 6-2. 95% significant correlation coefficients among room architectural parameters and acoustical measures at individual receiver locations in all of the lecture halls.

Figure 6-2 represents the 95% significant correlation coefficients among room architectural parameters and receiver specific acoustical measures in the lecture halls. The parameters associated with the size or shape of balcony were not used because there were no balconies in the lecture halls included in the study. An additional parameter Percentage of Ceiling and Wall Absorbent Surface ($P\alpha$) was added to account for the absorbent panels that were used in many of the lecture halls to reduce the room reverberation.

EDT10 and C80 were both strongly correlated with a large portion of the architectural parameters. Calculated Reverberation Time (RTs) or log(RTs) was correlated with EDT10 and C80 with $|r| > 0.9$.

In Chapter 5, a significant correlation was found between BR(EDT) and Average Absorption Coefficient (α). In this Chapter, this correlation in the lecture halls ($r = 0.73$) is much greater in magnitude than the correlation in the music halls ($r = 0.24$). The correlation between α and acoustical measures EDT10 (and C80) were also greater in magnitude in the lecture halls than those in the music halls. This is because the variations of average absorption coefficient in the lecture halls were larger than those in the music halls.

Room parameter Kch×TR(α) (Chair Type × Treble Ratio Based on Average Absorption Coefficient) was correlated with TR(EDT) ($r = 0.585$). The correlation between parameter TR(α) and acoustical measure TR(EDT) ($r = 0.372$) did not meet the significance level of 95 %. A comparison between values of the two variables suggested that TR(α) of the tablet-arm chairs was under estimated.

Statistical Relations in the Group of Music Halls

This set of analyses was centered around the statistical relations among architectural parameters and acoustical measures at individual receiver locations in the 14 music halls. The analyses related to acoustical measure IACC80 were presented with and without the measurements taken in hall M1 because a) the IACC80 values in hall M1 were the greatest among the IACC80 data taken in all halls and b) all the receiver locations used in hall M1 were near the central axis. Transformations of architectural parameters were studied and the ones that significantly increased the magnitude of correlation coefficients were presented.

Correlation Coefficients among Acoustical Measures and Receiver Parameters

Figure 6-3 represents the 98% significant correlation coefficients among receiver architectural parameters and acoustical measures at individual receiver locations in the music halls. The interaction parameters were also included. Table 6-1 summarized the rotated factor pattern of all of the receiver architectural parameters and the acoustical measures. Six common factors were found among all of the variables.

Receiver architectural parameters Distance to the Origin/Source (r) and log(r) were significantly correlated with acoustical measures EDT10, C80 and G. This agreed with Hook's finding. The parameter r/R (Distance to the Origin/Source / Average Distance to the Origin/Source) was not significantly correlated with acoustical measures EDT10 or C80. This suggested that the absolute distance rather than the relative distance determined acoustical measures EDT10 and C80. This can be attributed to variations of C80 and EDT among seats in a large size hall that are generally greater than those in a small size hall.

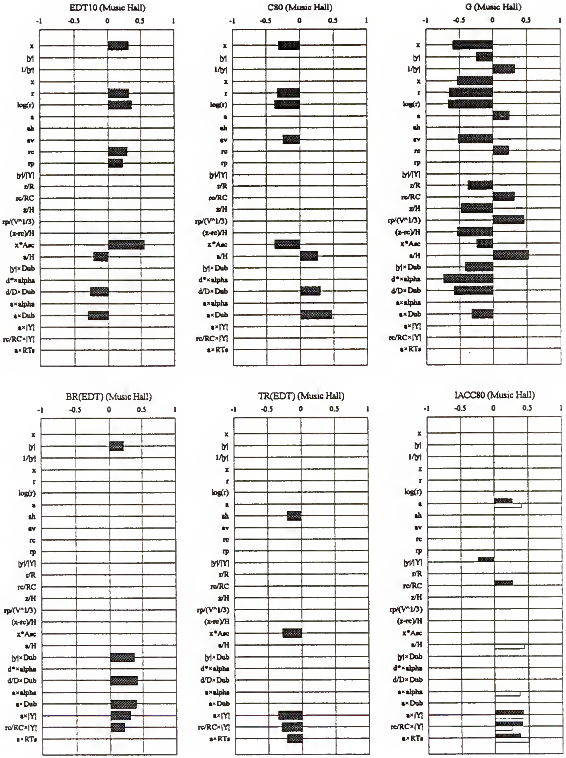


Figure 6-3. 98 % significant correlation coefficients among receiver architectural parameters and acoustical measures at individual receiver locations in all of the music halls (▨); in all of the music halls except hall M1 (☐).

Table 6-1. Rotated factor pattern of all of the receiver parameters and the acoustical measures for the music halls.

	1	2	3	4	5	6
rc	-0.880					
rp	-0.877					
rc/RC	-0.806				-0.299	0.273
(z-rc)/H	0.791	0.301	0.441			
$rp/(V^{1/3})$	-0.774				-0.498	
r/R×|Y|	-0.732					0.477
r/R	0.693		0.218		0.529	
av	0.603		0.442		0.440	
z/H	0.598		0.453		0.425	0.224
z	0.589		0.410		0.461	
|y|		-0.995				
|y|/|Y|		-0.931				
ah		-0.844			-0.396	
|y|×Dub		-0.737		0.385	0.248	
1/|y|		0.736				
a	-0.228	0.212	-0.886			
a×α			-0.870	0.221		
a×RTs			-0.794			
a×|Y|	-0.211		-0.783			0.432
a/H			-0.621		-0.487	
C80				**0.843**	**-0.226**	
EDT10				**-0.840**	**0.286**	
a×Dub	-0.321		-0.320	0.721	0.169	
r/R×Dub			0.279	0.586	0.574	
r×α	0.394				0.886	
x	0.326				0.879	
Log(r)	0.361				0.879	
r	0.405				0.872	
G					**-0.751**	
x×Asc			-0.401	-0.322	0.517	0.288
TR(EDT)		**0.243**			**-0.503**	
BR(EDT)				**0.484**	**0.502**	
IACC80			**-0.229**			**0.429**
Percentage Variance	19.6	14.9	11.4	9.5	19.31	4.6

Several architectural parameters that were orthogonal to one another were also significantly correlated with acoustical measures EDT10, C80 and G in addition to the correlations presented by Hook.

1. The parameter Vertical Angle of the Receiver (av) was correlated with acoustical measure C80 ($r = -0.254$). The C80 values were generally low at receiver locations on the side boxes in the Symphony Hall, Boston (hall O2),

Concert Hall of Kennedy Center (hall O5) and the Academy of Music (hall O6) where the Vertical Angles of Receivers (av) were the largest among all the receiver locations.

2. The parameter rc/RC (Distance to the Overhead Ceiling / Average Distance to the Overhead Ceiling) was correlated with acoustical measure G ($r = 0.321$). This correlation suggested that G is small when the receiver location is under a balcony because the parameter r/R was indicative of whether the receiver is on the main floor or under/over a balcony. However, the receivers located under or over the side box were the exceptions because these receivers were close to the sound source and the side boxes are generally not deep enough to reduce the early and reverberant sounds arriving at the seats underneath the side boxes.
3. The parameter Distance to Overhead Ceiling (rc) was correlated with EDT10 ($r = 0.292$). Parameter rc was, however, also significantly correlated with Average Audience Chamber Height (H) and the correlation coefficient between H and acoustical measure EDT10 was greater in magnitude ($r = 0.425$).

The correlations among acoustical measures BR(EDT) and the "raw" receiver architectural parameters were less significant than the correlation between BR(EDT) and the interaction parameters. This agreed with the results of the pilot study that the effects of the receiver parameters were dependent on the room parameters for acoustical measure BR(EDT). The same statements can also be applied to acoustical measure TR(EDT).

Angle of Incidence (*a*) was not significantly correlated with BR(EDT) at the 95 % significance level although the first pilot study suggested that parameter *a* was correlated with BR(RT) in three of the music halls.

IACC80 was significantly correlated with parameter |y|/|Y| (Absolute y Coordinate / Average Absolute y Coordinate) when the sample including hall M1 was used. This correlation agreed with Hook's finding. The receiver architectural parameter Angle of Incidence (*a*) was positively correlated with IACC80 based on both groups of rooms. Correlation coefficients equaled 0.271 with hall M1 included and equaled 0.404 without hall M1 included. This correlation may be attributed to the attenuation of direct sound in the 500 Hz band when the angle of incidence was small because the attenuation of the direct sound by the "seat dip" effect occurred in frequencies from 50 Hz to 500 Hz.

Table 6-2 summarized the representative architectural parameters of individual orthogonal factors for each acoustical measure. The parameters in the brackets were alternative parameters for each factor. About three or four orthogonal factors were correlated with each acoustical measure.

Table 6-2. Representative architectural parameters of individual orthogonal factors for each acoustical measure based on the data measured in the music halls.

EDT10	C80	G	BR(EDT)	TR(EDT)	IACC80 (with hall M1)	IACC80 (without hall M1)
rc, [rp]	av	rc/RC, [(z-rc)/H]	|y|, [|y|×Dub]	ah	|y|/|Y|	r/R×|Y|, [a×|Y|]
a×Dub	a×Dub	|y|, [(z-rc)/H]	a×|Y|	a×|Y|, [a×RTs]	r/R×|Y|, [a×|Y|]	a, [a×|Y|]
log (r)	log(r)	r/R×Dub	a×Dub, [r/R×dub]	r/R×|Y|	a, [a×|Y|]	
x×Asc		r×α, [log(r)]				

Regression Models

Multiple regressions were conducted for each acoustical measure. The regressors were the receiver architectural parameters summarized in Table 6-2 and the selected room architectural parameters that were significantly correlated with the corresponding acoustical measures.

Table 6-3. Regression models for each acoustical measures calculated based on the data taken in the music halls.

Regression Models		R^2 in % total/partial	STD of Residuals	Remarks
EDT	$0.825 + 0.578\times RTs - 0.0007\times a\times Dub + 0.0048\times Pwd - 3.83\times\alpha + 9.7\times10^{-5} * x\times Asc$	85 / 65	0.18 sec	
C80	$8.1 - 3.0\times RTs - 0.0215\times Pcdt - 0.064\times av + 0.04\times Dub$	80 / 45	1.0 dB	
	$7.34 - 6.6\times EDT10 + 2.9\times avg\ (EDT10) - 0.7\times Ksb$	89 / 82	0.7 dB	
	$-3.55 + 1.03\times C80b\_edt - 0.66\times Ksb - 0.05\times av + 2.1\times \log(r)$	79 / 72	1.1 dB	
G	$16.5 - 0.24\times d\times\alpha - 0.07\times Dub - 2.5\times Ksb - 31\times\alpha$	80 / 56	1.6 dB	
	$16 - 0.23\times d\times\alpha - 1.17\times Dub/Hub - 2.36\times Ksb + 31.3\times\alpha + 0.74\times rc/RC$	83 / 60	1.6 dB	A
	$11 + 0.3\times Gb\_rt - 0.06\times r/R\times Dub - 2.34\times Ksb - 40\times\alpha + 1.05\times rc/RC$	83 / 66	1.5 dB	
	$1.82 + 0.054\times Gb\_edt + 0.96\times rc/RC + 3.63\times avg(EDT10) - 9.9\times10^{-6}\times V - 0.15\times r\times\alpha$	78 / 71	1.6 dB	
BR	$0.76 + 0.06\times BR(\alpha) + 0.0025\times W + 0.01\times std(ah) - 0.08\times Ksb + 0.03\times Dub$	66 / 32	0.070	
TR	$1.07 - 0.001\times * W - 0.0009\times Asw - 0.0012\times WH/Lmax$	47 / 30	0.043	
	$1.19 - 6.5\times10^{-4}\times W - 0.0015\times Asw - 0.03\times Sa/N - 0.0017\times Asc + 0.0005\times Pwd$	67 / 30	0.035	
IACC	$-0.513 + 0.092\times Sa/N + 0.018\times a + 0.0058\times\lvert Y\rvert$	49 / 30	0.100	
	$0.018 + 0.023\times Hub + 0.46\times a/H - 4.4\times10^{-5}\times Awp\times W - 0.02\times Af$	52 / 17	0.117	B

A. Rooms with balcony only (hall M3 removed)
B. Hall M1 removed

Table 6-3 summarizes the regression models derived for each acoustical measure based on the data taken in the music halls. A 98 % significance level was used as the variable entry criterion in the regression procedures. The models presented were selected based on a number of trials. The models were selected that contained most of the orthogonal major factors presented previously.

The Calculated Reverberation Time (RTs) only explained 65% of the variance of acoustical measure EDT10. The explained variance was increased by 20% when several architectural parameters were included in the model.

The architectural parameters included in addition to Calculated Reverberation Time (RTs) explained a significant amount of the variance of acoustical measure C80, whereas RTs alone explained only 45 % of the variance. The Calculated C80 Using hall average values of EDT10 based on Barron's Formula (C80b_edt) explained 72% of the variance of C80. The percentage of the explained variance was increased by 7% when the parameters Logarithm of Distance to the Origin/Source(log(r)), Vertical Angle of the Receiver (av), and Side Box Design (Ksb) were added in addition to C80b_edt. The total explained variance, however, is less than the 82 % explained only by the receiver specific values of EDT10.

The architectural parameter $r \times \alpha$ (Distance to the Origin/Source × Average Absorption coefficient) alone explained 56 % of the variance of acoustical measure G. The Calculated G based on Barron's formula, using either Calculated Reverberation Time (RTs) or hall average values of Early Decay Time (EDT10), increased this percentage to more than 66 %. However, this is still not a high percentage. The remaining un-explained portion of the variance were explained by the architectural parameters such as Under-Balcony Depth (Dub), Side Box Design (Ksb) and r/R (Distance to Overhead Ceiling / Average Distance to Overhead Ceiling). The room architectural parameter Dub was expected to be included in the model because halls with deep balconies have been suggested by Barron to be one of the situations where his revised theory can not be applied. (Barron, 1988).

Neither the model for BR(EDT) nor the models for TR(EDT) contained any receiver architectural parameters or interaction parameters because none of these parameters meet the significance level to enter the regression procedures. This was expected because of the low correlation coefficient between the "raw" receiver architectural parameters and these two acoustical measures.

The percentages of explained variance by the two models for IACC80 were only around 50%. Part of the un-explained variance can be attributed to random errors because it has been suggested that IACC80 is sensitively affected by a) objects that surrounded the manikin head or the sound source and b) minor changes of orientation of the head (Siebein et al, 1993). These affects actually occurred while the binaural measurements were taken. In addition, the number of receiver location used in each room may not have been large enough to represent how IACC80 changes within a room.

The standard deviations of residuals were compared to the confidence intervals summarized in Table 3-3 to determine whether it is necessary to derive more accurate models. The 1/4 average confidence interval of acoustical measures EDT10, BR(EDT) and IACC80 at individual receiver locations was fairly small relative to the standard deviations of residuals of the regression models. This indicated that other potential parameters may be found that are highly correlated with the three acoustical measures.

The unexplained variance of BR(EDT), TR(EDT), and IACC80 can also be attributed to the relations between receiver architectural parameters and acoustical measures on rooms that varied from room to room.

Statistical Relations in the Group of Lecture Halls

This set of analyses was centered around the statistical relations among architectural parameters and acoustical measures at individual locations in the 8 lecture halls. Analyses related with IACC80 were not conducted because binaural measurements were only taken in four of the lecture halls.

Correlation Coefficients among Acoustical Measures and Receiver Parameters

Figure 6-4 represents the 95 % significant correlation coefficients among receiver architectural parameters and acoustical measures in the lecture halls. The interaction parameters were also included. A 95 % significant level was used because the 25 receiver locations sampled in the lecture halls is much less than the 131 receiver locations sampled in the music halls. The number of receiver parameters that were significantly correlated with acoustical measures in the lecture halls was much less than the number in the music halls. Table 6-4 summarizes the rotated factor pattern of all of the receiver architectural parameters and the acoustical measures. Five significant common factors were found among all of the variables.

The receiver architectural parameter Distance to Origin/Source (r) was significantly correlated with acoustical measures EDT10 and G yet not with C80. In fact, C80 was not significantly correlated with any of the architectural parameters grouped by factor 1. The poor correlation between r and acoustical measure C80 can be attributed to the total energy of early reflections arriving after the direct sound and before 80 ms was large relative to the energy of the direct sound because the small room size of the lecture halls. Therefore, the distance which determines the magnitude of the direct sound is not as important as it would be in a large size hall.

The relation between parameter r and acoustical measure G agreed with Hook's finding. The relations between of |y| (or 1/|y|) and EDT and between |y| (or 1/|y|) and C80 were not found by Hook. This disagreement can be attributed to the large room length to room width ratio of the hall included in Hook's study. Similar to the findings in the study of the music hall group, the relative distance r/R (Distance to the Origin/Source / Average Distance to the Origin/Source) was not significantly correlated with either EDT10, C80 , or G. The correlation coefficients between parameter $r\times\alpha$ (Distance to Origin/Source × Average Absorption Coefficient) and acoustical measure G was greater in magnitude than the correlation coefficient between parameter r and acoustical measure G.

Both EDT10 and C80 were significantly correlated with parameter Distance to Overhead Ceiling (r) and $a\times\alpha$ (Angle of Incidence × Average Absorption Coefficient). The effect of r was found previously in the music halls. The effect of $a\times\alpha$ can be considered as similar to the effect of α because the two architectural parameters were significantly inter-correlated for the receiver locations used in the lecture halls.

Acoustical measure G was also correlated with receiver architectural parameter Distance to Perimeter (rp). The negative correlation (r = -0.429) suggested that when receiver was near a surface, the early reflections from the surface would increase the overall Level (G).

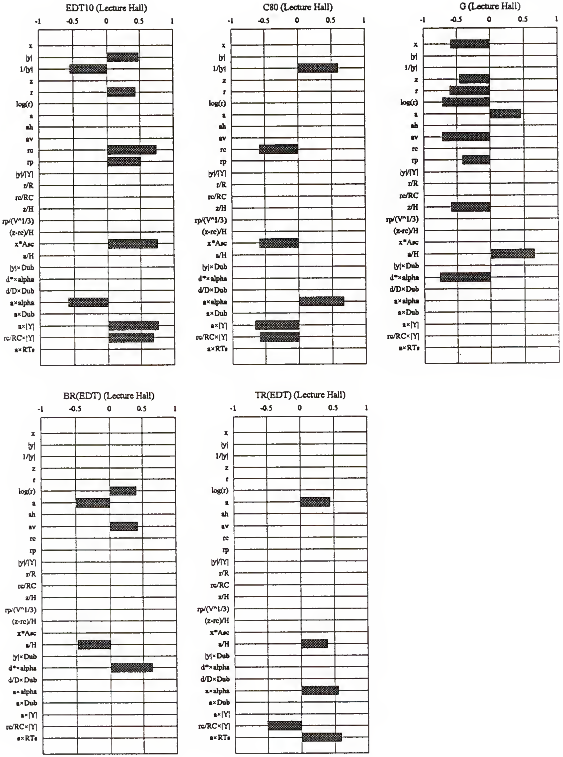


Figure 6-4. 95% significant correlation coefficients among receiver architectural parameters and acoustical measures at individual receiver locations in the lecture halls.

Table 6-4. Rotated factor pattern of all of the receiver parameters and the acoustical measures for the lecture halls.

	1	2	3	4	5
z	0.908				
z/H	0.905				
x	0.854	0.464			
rc/RC	-0.831				
r^2	0.802	0.500			
av	0.800				
r	0.799	0.523			
r/R	0.734				
Log(r)	0.715	0.475			
r×α	0.705			0.614	
$rp/(V^{1/3})$	-0.565		-0.625		
a×Y		0.913			
r		0.893			
rp		0.871			
EDT10		**0.864**			
r/R×|Y|		0.860			
x×Asc	0.524	0.773			
C80		**-0.732**		0.524	
|y|/|Y|			0.927		
ah			0.882		
|y|			0.864		
1/|y|			-0.656		
BR(EDT)				**0.909**	
G	**-0.377**		**-0.741**		
TR(EDT)					**-0.773**
a×α		-0.407			-0.695
a×RTs					-0.674
a	-0.389		-0.386	-0.692	
a/H	-0.387			-0.439	-0.617
Percentage Variance	28.1	23.8	16.5	10.3	8.4

Parameter Angle of Incidence (*a*) was the only "raw" receiver parameter that was correlated with acoustical measures BR(EDT) and TR(EDT). However, architectural parameter "a" is significantly correlated with Average Absorption Coefficient (α).

Table 6-5 summarized the representative architectural parameters of individual orthogonal factors for each acoustical measure. The parameters in brackets were the alternative parameter for each orthogonal factor. All of the acoustical measures except EDT10 were significantly correlated with three factors.

Table 6-5. Representative architectural parameters of individual orthogonal factors for each acoustical measure based on the data measured in the music halls.

EDT10	C80	G	BR(EDT)	TR(EDT)
r^2	$rc, [a\times\vert Y\vert]$	$\log(r), [r\times\alpha]$	$\log(r), [r\times\alpha]$	$r/R\times\vert Y\vert$
$rc, [a\times\vert Y\vert]$	$1/\vert y\vert$	$a/H, [r\times\alpha]$	$a, [r\times\alpha]$	a
$1/\vert y\vert$	$a\times\alpha$	rp	a/H	$a\alpha$
$a\times\alpha$				

Regression Models

Table 6-6 summarizes the regression models of each acoustical measure based on data taken in the lecture halls. As mentioned previously, the models presented were selected from a numbers of trials. A 95 % significance level was used as the variable entry criterion in the regression procedures.

Most of the models contained less than four variables (architectural parameters). The number of variables was generally less than the number of variables contained in the models presented for the music halls because the sample size was much smaller.

Three models were presented for acoustical measure EDT10. The parameter Calculated Reverberation Time (RTs) alone explained 90 % of the variance of EDT10. The other models that contained architectural parameters other than the Calculated Reverberation Time (RTs) did not significantly improve the percentage of explained variance, yet the model with 98 % explained variance reduced the standard deviation of variations from to 1.8 sec to 0.9 sec.

Table 6-6. Regression models for each acoustical measure based on data taken in the lecture halls.

	Regression Models	R^2 in % total/partial	STD of Residuals
EDT	$0.30 + 0.84\times \mathrm{RTs}$	90 / 90	0.18 sec
	$0.468 + 0.56\times \mathrm{RTs} + 0.033\times \mathrm{Asc}$	94 / 90	0.14 sec
	$1.19 + 0.135\times \mathrm{RTs} + 0.06\times \mathrm{Asc} - 2.9\times\alpha + 0.04\times \mathrm{WH/Lmax}$	98 / 90	0.09 sec
C80	$2.21 - 12.6\times\log(\mathrm{RTs}) + 2.58\times 1/\lvert y\rvert$	90 / 88	1.2 dB
	$5.9 - 5\times \mathrm{EDT10} + 12.3\times\alpha + 0.005\times\lvert y\rvert\times \mathrm{Asc} + 2.57\times 1/\lvert y\rvert$	96 / 88	0.8 dB
	$-0.023 + 0.721\times \mathrm{C80\_rt} + 2.8\times 1/\lvert y\rvert$	91 / 88	1.1 dB
	$-0.624 + 0.665\times \mathrm{C80b\_rt} + 2.66\times 1/\lvert y\rvert$	89 / 87	1.2 dB
	$0.027 + \mathrm{C80b\_edt}$	97 / 97	0.7 dB
G	$21.4 - 1.11\times r\times\alpha - 0.15\times \mathrm{Aw} - 0.2\times \mathrm{rp} - 0.096\times W$	94 / 59	1.2 dB
	$-0.09 + 0.91\times \mathrm{Gb\_rt} - 0.115\times \mathrm{Aw} + 0.04\times \mathrm{Asw}$	94 / 81	1.0 dB
	$-0.93 + 0.903\times \mathrm{Gb\_edt}$	83 / 83	1.8 dB
	$-4.67 + 1\times \mathrm{Gb\_edt} - 0.1\times \mathrm{Aw} + 0.067\times W$	93 / 83	1.1 dB
BR	$0.16 + 1.52\times\alpha + 0.19\times\log(V)$	78 / 54	0.078
	$0.265 + 0.84\times P\alpha + 0.71\times\log(V) - 0.02\times a$	78 / 39	0.074
	$-0.22 - 0.013\times \mathrm{Sa/N} - 0.54\times\log(\mathrm{RTs}) + 0.30\times\log(V)$	78 / 26	0.079
	$-0.36 - 0.11\times a + 0.069\times \mathrm{BR}(\alpha) + 0.31\times\log(V) - 0.46\times\log(\mathrm{RTs})$	80 / 24	0.075
TR	$0.97 - 0.0052\times\lvert \mathrm{AH}\rvert + 0.115\times \mathrm{Kch}\times \mathrm{TR}(\alpha)$	59 / 37	0.048
	$0.949 + 0.0025\times \mathrm{WH/Lmax} + 0.126\times \mathrm{Kch}\times \mathrm{TR}(\alpha) - 0.0064\times \mathrm{AH}$	59 / 40	0.048

The architectural parameter Calculated Reverberation Time (RTs) also explained a high percentage of the variance of C80 (88 %). The percentage of explained variance was improved slightly when parameter $1/|y|$ (1 / Average Absolute y Coordinates) was added.

The Calculated C80 Using EDT10 Based on Barron's Formula (C80b_edt) explained 97 % of the variance of C80 with a slope equal to one. The percentage of explained variance was less (87 %) when Calculated Reverberation Time (RTs) was used to replace EDT10.

Receiver parameter r×α (Distance to the Origin/Source × Average Absorption Coefficient) explained only 59% of the variance of acoustical measure G. Calculated G based on Barron's Formula, using either the calculated reverberation or the measured early decay time (EDT) explained more than 81% variance of G. However, the percentages of explained variance of all the models presented were increased to approximately 93% when architectural parameter were used in addition to Room Volume (V), Calculated Reverberation Time (RTs), d*α (Distance to the Origin/Source / Average Absorption Coefficient). These additional parameters included Average Side Wall Angle (Aw), Average Stage Side Wall Angle (Asw), Average Audience Chamber Width (W) and Distance to the Perimeter (rp).

Several models of BR(EDT) were presented because of the high correlation among the architectural parameters that were significantly correlated with BR(EDT). These inter-correlated parameters included Sa/N (Total Seating Area / Number of Seats), Angle of incidence (*a*), Average Absorption Coefficient (α), Bass Ratio based on Average Absorption Coefficient (BR(α)), and Percentage of Ceiling or Wall Absorption Surface (Px). The relation between Sa/N and BR(EDT) can be attributed to the large distance between two seats in the same rows in two classrooms (hall C2 and C3) that absorbed low frequency sound. This was not accounted for by the generalized absorption coefficient for the tablet-arm seats. Room Volume (V) and Calculated Reverberation Time (RTs) represented the other major factors that explained a significant portion of the variance of BR(EDT).

The percentages of explained variance of the two models of TR(EDT) were only

59 %. Receiver parameter Angle of Incidence (*a*) did not meet the significance level to enter the regression procedure.

A comparison was made between the standard deviations of residuals of all models and 1/4 of average 95% confidence interval of the acoustical measures summarized in Table 3-3. The standard deviations of residuals of the models for BR(EDT) and TR(EDT) were much larger than the 1/4 average confidence intervals. This suggested that more accurate models may possibly be derived for the two acoustical measures.

A Comparison of The Group of Music Halls to The Group of Lecture Halls

Apparent differences of statistical relations were found between the two groups of halls. This was expected because the relative hall standard deviations of acoustical measures for the music halls were generally larger than those for the lecture halls.

Differences of Explained Variance

Figure 6-5 showed the percentage of explained variance for each acoustical measure by several major architectural parameters comparing the music hall group to the lecture hall group.

The parameter Calculated Reverberation Time (RTs) explained much more variance in the lecture halls than in the music halls. This may be because calculations were more accurate in the small lecture halls with simple shapes and only a few surfaces than in the large music halls.

Calculated estimates based on Barron's revised theory explained less percentage of variance of acoustical measure C80 and G in the music halls (72 % for C80 and

71% for G) than in the lecture halls (97 % for C80 and 83 % for G). This agreed with Barron's suggestion that his revised theory was accurate for rooms with a limited set of architectural characteristics. These architectural characteristics can be generally found in the group of lecture halls except a few rooms have significant amount absorbent surfaces.

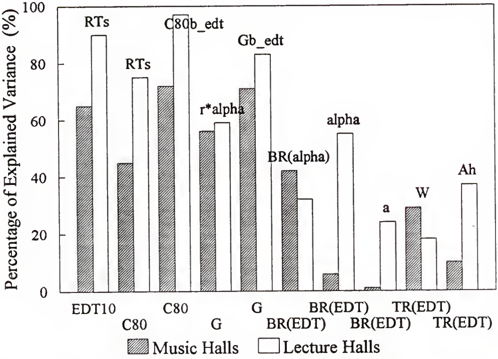


Figure 6-5. The percentage of explained variance for each acoustical measure by several major architectural parameters comparing the music hall group to the lecture hall group.

The variance of acoustical measure BR(EDT) was primarily explained by Bass Ratio Based on Average Absorption Coefficient (BR(α)) in the music halls where the parameter BR(α) was primarily determined by a) the type of seats, b) the amount of carpet, and c) the rigidity and thickness of the major reflective surfaces . In the lecture halls, acoustical measure BR(EDT) was primarily determined by a) the

Percentage of Ceiling or Wall Absorption Surfaces (Pα) that were used to reduce Reverberation Time and b) Angle of Incidence (*a*).

As stated previously, the variance of acoustical Measures TR(EDT) was primarily explained by the parameter Kch×TR(α) (Type of Chair (Kch) × Treble Ratio based on Average Absorption Coefficient) in the lecture halls while the correlation between TR(α) and acoustical measure TR(EDT) in the music halls was insignificant. Other than this difference, acoustical measure TR(EDT) in both groups of halls was primarily determined by similar architectural parameters that were associated with the width of the audience chamber such as Average Audience Chamber Width (W) and Average of Absolute Horizontal Angle of Receivers (|AH|).

Predictability of Regression Models for the Group of Music Halls

Many of the differences of statistical relations found in this study can be attributed to the major differences of architectural characteristics stated in the beginning of this chapter. For example, receiver architectural parameter Distance to Overhead Ceiling (rc) and Vertical Angle of Receiver varied significantly in rooms with balconies. The scatter plot on the left side of figure 6-6 shows that the magnitude of variation of architectural parameter rc/RC (Distance to Overhead Ceiling / Average Distance to Overhead Ceiling) is much larger in the music halls than in the lecture halls. Parameter rc/RC was correlated with acoustical measure Overall Level (G) with a greater magnitude in the music halls than in the lecture halls. Architectural parameter rc/RC differentiates the seats under or over balconies from the seats in the main space in a room with balconies. The graph on the right hand side of figure 6-6 shows more clearly the positive correlation between acoustical measure G and architectural parameter rc/RC when the concert halls (including the multi-use halls used in concert mode) and the churches were represented by different symbols because the churches are typically smaller than the multi-use halls and the concert halls.

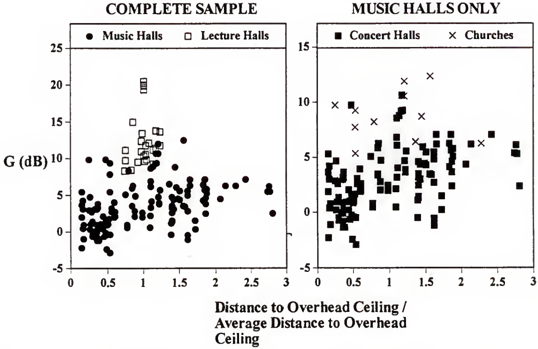


Figure 6-6. Scatter plots of Overall Level as a function of rc/RC (Distance to Overhead Ceiling / Average Distance to Overhead Ceiling).

The effect of receiver architectural parameter Vertical Angle of Receiver (av) on acoustical measure Clarity Index (C80) can be found particularly in the halls with side boxes. Figure 6-7 shows the differences of C80 between seats near the central axis of the rooms and the seats located under or over the side boxes in Symphony Hall in Boston (hall O3) (left) and the Academy of Music in Philadelphia (hall O6) (right). The differences of C80 between the two zones of seats generally increase with an increase of balcony height.

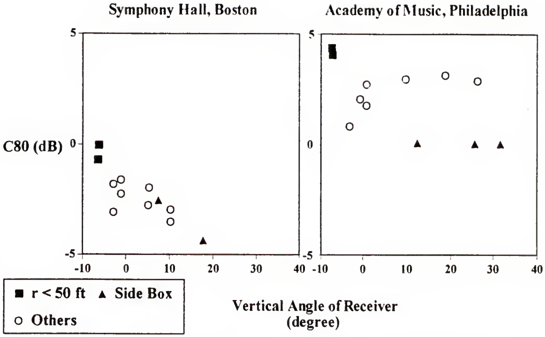


Figure 6-7. Scatter plots of Clarity Index (C80) as a function of architectural parameter Vertical Angle of Receiver (av) in Symphony Hall in Boston (hall O3) (left) and Academy of Music in Philadelphia (hall O6) (right) .

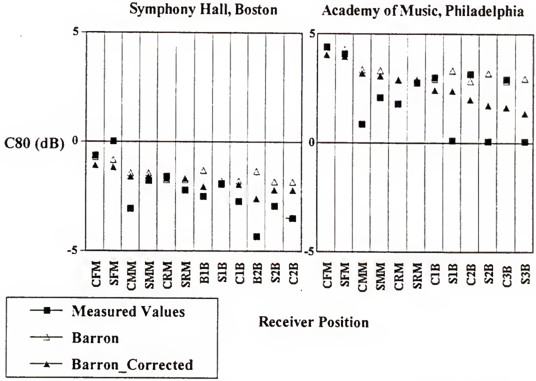


Figure 6-8. Comparison of measured Clarity Index (C80) to Estimates based on Barron's theory and regression models derived in the current study.

Figure 6-8 shows that the differences between the two zones of seats were not reflected by the Calculated C80 Using on EDT based on Barron's Theory (C80b_edt). C80b_edt for the receiver locations near the central axis is smaller than C80b_edt for the locations at the side boxes while the relation of measured values between the two zones is just the opposite. The inclusion of architectural parameters in the regression in addition to C80b_edt corrected part of the discrepancy and decreased the largest residual to an acceptable value of approximately two dB.

However, previous studies suggested that such differences of acoustical characteristics among zones of audience seats can be accurately assessed by acoustical measurements made in scale models with reasonable details (Siebein, 1986; Chiang 1991). This indicates that using measurements made in scale models is more adequate than using the regression models derived in the current study at very late stages of the design process.

CHAPTER 7

CONCLUSIONS

There are five major conclusions of this study.

1. A method was developed to quantitatively document detailed architectural characteristics of rooms that have been suggested to affect the acoustical quality of rooms. A set of parameters were proposed based on these architectural details. This set of parameters reasonably explained much of the variance (50 % ~ 98 %) of the acoustical measures taken at individual locations in a variety of rooms as well as the hall averages and standard deviations of acoustical measures of the rooms.
2. The results of this study not only confirmed the findings presented by Gade, Hook, Bradley, and Barron where similar approaches were used, but also identified many more orthogonal architectural parameters that are significantly correlated with the acoustical measures. The number of orthogonal factors that explained the primary variance of each specific acoustical measure varied from two to six. The inclusion of several additional factors is more representative of the actual considerations of room acoustic qualities during the design of buildings than the one or two factors contained in the models presented in these previous studies.

3. The analyses related to the hall standard deviations of acoustical measures quantified many of the design principles associated with sound diffusion stated in literature.
4. The multiple regression models can be applied to room acoustical design although the results of the study inevitably depend on the selection of the halls. This is because conservative criteria were used to select representative architectural parameters and to derive regression models.
5. Sub-grouping of the rooms successfully identified more significant relations among architectural parameters and acoustical measures by including additional architectural parameters that were specific for each group of rooms. For example, the parameter defining the percentage of ceiling and wall absorbent surfaces was used specifically for the group of lecture halls. More architectural parameters were required to estimate the acoustical measures for the group of music halls than for the group of lecture halls because the interior shapes of music halls were generally more complex than those of the lecture halls.

The relationships among room architectural parameters and the hall average of acoustical measures generally agreed with the results of Gade's studies (Gade, 1988; Gade, 1990; Gade, 1991). Much more information was derived based on the statistical relations among acoustical measures and the architectural parameters than those presented by Gade:

1. The regression models containing no calculated estimates of acoustical measures were as accurate as the models that contained these estimates. The

models without the calculated estimates based on measured reverberation time can be implemented in schematic design and design development phases of a project.

2. Each acoustical measure was related to architectural parameters grouped by a few major orthogonal factors that were additional and orthogonal to the architectural parameters presented by Gade. Major relations were identified between:
    a). acoustical measure EDT10 (also C80) and architectural parameter Stage Ceiling Angle (Asc) indicating the importance of the shape of the stage ceiling on the reverberation time in a room;
    b). acoustical measure G and architectural parameter Dub/Hub (Average Under-Balcony Depth / Average Under-Balcony Height) indicating the importance of the relative depth of the under-balcony space on the relative loudness in a room where early reflections would be blocked by relatively deep balcony but created by relatively shallow balconies.
    c). acoustical measure BR(EDT) and Audience Chamber Width (W) indicating the importance of the overall room width on the bass ratio in a room;
    d). acoustical measure TR(EDT) and Average Absolute Horizontal Angle of Receivers (AH) indicating the importance of the width of room relative to the length of room on the treble ratio in a room; and
    e). acoustical measure IACC80 and Average Under Balcony Height (Hub)

indicating the importance of the height of the under-balcony opening on the inter-aural cross correlation in a room with balconies.

The absorption coefficients of seats used in this study, however, were not significantly correlated with acoustical measure TR(EDT). A significant correlation was identified between this acoustical measure and a qualitative variable used to distinguish tablet-arm chairs from theater chairs. This indicates a need for more accurate absorption coefficient data for various types of seats.

The variance of the hall standard deviation of acoustical measures can be explained by a few groups of room architectural parameters that confirmed many of the fundamental design principles stated in books on room acoustics. The architectural parameters associated with room size such as Room Volume (V) and the parameters associated with balcony configuration such as Dub/Lmax (Average Under Balcony Depth / Maximum Audience Chamber Length) were highly correlated with most of the monaural acoustical measures, i.e., all six measures except IACC80. The effect of the room size can be related to the mean free path of sound prorogation in a hall. The effect of the balcony can be attributed to the effect of a "sound shadow" and coupled room effects for the seats underneath a deep balcony while balcony faces would reflect sounds back to the seats on the main floor. A shallow balcony located high above the seats can create desirable early sound reflections in the transverse plane. The parameters associated with the amount or the size of diffusing surfaces, such as the Percentage of Side Wall Diffusing Surface (Pwd), were significantly correlated with acoustical measures TR(EDT) and IACC80. Nevertheless, the results of the study related to the hall standard deviations of acoustical measures were limited by the large confidence interval of the hall standard deviations of acoustical measures of a few small size halls where acoustical measurements were taken at only two receiver locations. The analyses suggested a need to use at least five to six receiver locations in a room no matter how large the room is.

Significant differences of statistical relations among architectural parameters and receiver specific acoustical measures were found between the group of music halls and the group of lecture halls. Barron's revised theory, although proposed for concert halls, was found to provide more accurate estimations for acoustical measures C80 and G for receiver locations in the lecture halls than in the music halls. A few orthogonal architectural parameters, such as Relative Distance to Overhead Ceiling (rc/RC) and Average Under-Balcony Depth (Dub), quantified many of the architectural characteristics suggested by Barron. These parameters also explained much of the variance of acoustical measures in addition to those explained by the calculated estimates based on Baron's formulas.

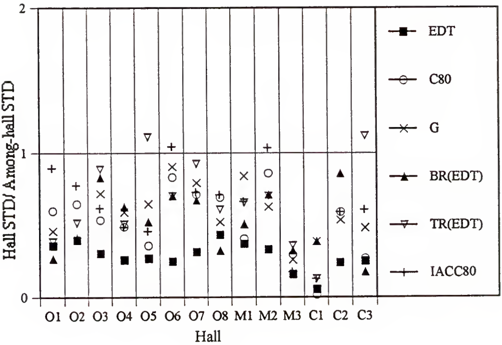
More accurate regressions may possibly be derived for acoustical measures BR(EDT, TR(EDT), and IACC80 in the future by identifying how the statistical relations between receiver architectural parameters and these acoustical measures are dependent on room architectural characteristics. Nevertheless, two relations among architectural parameters and IACC80 at receiver locations in the music halls agreed with current design theories proposed by acoustical consultants: a). the effect of Side Balcony Design (Ksb) agreed with the design theory that the existence of side boxes created second order lateral reflections which decreased the Inter-aural Cross Correlation (Johnson, 1992) and b). the effect of parameter Awp*W (Average Audience Chamber Side Wall Panel Angle * Average Audience Chamber Width) agrees with the design principle that a reverse fan-shaped plan of a hall would enhance lateral refections (Marshall, 1992).

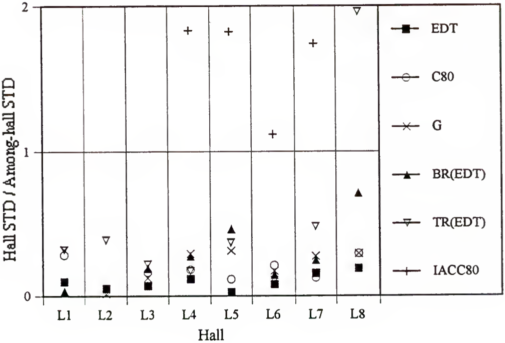
The development of a comprehensive set of architectural parameters is one of the major contributions of this study because few studies have integrated various architectural characteristics to represent many of the actual design considerations involved in room acoustics design. The results of this study provide acoustical consultants with the regression formulas to predict acoustical measures without using computer models or scale models. This practical application can be used progressively in various phases of design depending upon what types of architectural data are available and what magnitude of accuracy is expected. During schematic design phase, the average and variation among seats of the acoustical measures can be estimated very simply. Later in the design process, the values of the acoustical measures can be estimated for individual seating locations in the room. This study also revealed insights into the significance of many effects of architectural parameters on the acoustical measures of a room that future research can investigate more details using other method such as scale model tests. Future studies are suggested to expand the single sound source used in the present study to multiple sources that represent a group such as an orchestra or a choir. Future studies are also suggested to include halls that incorporate many of the newer architectural features that have been proposed by acoustical consultants in recent years. These might include upper side walls inclined in the vertical plane, terraced seating areas and reverberation chambers.

APPENDIX A

HALL STANDARD DEVIATIONS OF ACOUSTICAL MEASURES

The graphs in figure A-1 represent the ratios of the hall standard deviations of acoustical measures to the among-hall standard deviations of acoustical measures for the music halls (top) and the lecture halls (bottom). The among-hall standard deviations of acoustical measures are the standard deviations of the hall average acoustical measures for individual groups of halls. The ratios for all acoustical measures except Early Decay Time (EDT10) generally varied from 0.5 to 1.2.





Figures A-1. Ratios of the hall standard deviations of acoustical measures to the among-hall standard deviations of acoustical measures for the music halls (top) and the lecture halls (bottom).

APPENDIX B

ARCHITECTURAL DATA FORM (COMPLEX SPACE)

Architectural data were measured manually from plan and section drawings of the halls, mostly at a scale of 1/8"=1'0"or 1/16"=1'0", and were later entered into Lotus spreadsheets. Two forms were developed to record measurements: a simple form was designed for small size halls where no balconies exist and a complex form was used for large size halls including churches, multi-use halls and concert halls.

Figure B-1 shows the complex form used for large size halls. Data shown were measured and computed based on the drawings of Symphony Hall in Boston. Shaded values were computed automatically by the spreadsheet. Areas of individual surfaces and room volume were manually calculated before entered to the spreadsheet. The terms used in the form corresponded to the terms listed in Table 4-1.

ARCHITECTURAL PROPERTY DATA 3/27,'93 FORM CONC-(m>3/4b)

General Assumption: 1. Symetrical Design 3. A Center Sound Source
2. Not an Arena

ROOM: **Boston Symphony Hall** Data taken by Wei-hwa Chiang

SHAPE (a) Rectangle
Square
Fan
Reversed Fan
Diamond
Partial Fan
Partial reversed fan
Houseshoe
Circle
[✓ Ellipse]

(b) # of balcony 2
(c) [✓ No proscenium]
Proscenium
- No Shell
Shell

USE [✓ Concert hall]
Recital hall
Theater (Opera)
Theater (Drama)
Multi-use
Chapel
Lecture/Meeting
Others

The coordinate:
1. The center sound souce is (0,0)
2. the line along the central axis at the source height is the x axis

***** Shaded cells don't neet to be filled out. Some of them will be computed by the computer. ****

PROPERTIES OF INDIVIDUAL RECEIVERS

	location	x	y	z	d-c. source
2nd sound source	left	-14.4	13.4	0.5	19.7
3rd sound source	right	-7.3	-13.4	0.2	15.3

Reciver Coordinates in ft (47 in. above)

	location	floor level	x	y	z at floor	z	d	d(s2)	d(s3)
r1	CFF								
r2	CFM	1	48.0	-5.8	-9.4	-5.7	48.7	65.6	56.1
r3	SFM	1	43.8	-26.6	-9.4	-5.7	51.5	70.9	53.1
r4	CMM	1	75.0	-6.3	-7.7	-4.0	75.3	91.6	82.7
r5	SMM	1	72.0	-26.5	-7.7	-4.0	76.8	95.2	80.5
r6	CRM	1	110.6	-4.4	-6.0	-2.3	110.7	126.2	118.2
r7	SRM	1	109.2	-26.5	-6.0	-2.3	112.3	129.9	117.2
r8	B1B	2	58.6	-33.5	5.1	8.8	68.0	87.1	69.4
r9	B1S	2	111.4	-29.3	6.7	10.4	115.6	133.2	120.1
r10	B1C	2	116.2	-5.8	6.7	10.4	116.8	132.3	124.1
r11	B2B	3	58.5	-34.8	17.7	21.4	71.3	89.8	72.3
r12	B2S	3	122.7	-30.3	19.3	23.0	128.4	145.6	133.0
r13	B2C	3	127.4	-6.7	19.3	23.0	129.7	145.0	136.8
r14									
AVG		1.75	87.76	-19.70	2.38	6.05	92.10	109.37	96.97
STD		0.83	29.96	12.01	11.08	11.08	28.43	27.65	29.52

Receiver to Ceiling Distance in ft

	r1	r2	r3	r4	r5	r6	r7	average
Main ceiling to fl. slab		60.6	60.6	59.3	59.3	9.2	9.2	
Main ceiling to receivr.		56.9	56.9	55.6	55.6	5.5	5.5	34.5
	r8	**r9**	**r10**	**r11**	**r12**	**r13**	**r14**	**std**
Main ceiling to fl. sla	8.7	45.7	45.7	34.3	32.8	32.8		
Main ceiling to receiv	5.0	42.0	42.0	30.6	29.1	29.1		19.6

Angle in degree

	r1	r2	r3	r4	r5	r6	r7	average
Horizontal		-6.9	-31.3	-4.8	-20.2	-2.3	-13.6	-14.5
Vertical		-6.8	-6.4	-3.1	-3.0	-1.2	-1.2	2.8
	r8	**r9**	**r10**	**r11**	**r12**	**r13**	**r14**	**std**
Horizontal	-29.8	-14.7	-2.9	-30.7	-13.9	-3.0		10.7
Vertical	7.4	5.1	5.1	17.4	10.3	10.2		7.3

	r1	r2	r3	r4	r5	r6	r7
Long. floor slope		2.5	2.5	3.5	3.5	5.0	5.0
	r8	**r9**	**r10**	**r11**	**r12**	**r13**	**r14**

Figure B-1. The architectural data form used for large size halls.

PROPERTIES OF THE ROOM

Parimeter Coordinates in ft

	x	p0 main floor coordinate (center) z	p1 main floor half width |y|	p1 main floor coordinate (side) z	p2 balcony coordinate (at y(p1)) z	p3 balcony coordinate (side) |y|	p3 balcony coordinate (center) z	p3 balcony coordinate (side) z
@ stage rear wall	-26.8	-4.4	22.5	-4.4		22.5		
@ sound source	0.0	-5.4	31.0	-5.4		31.0		-5.4
@ proscenium	0.7	-5.4	36.5	-5.4		36.5		
@ apron	5.5	-9.3						
@ orchestra pit								
@ 1/4 point	34.9	-9.3	37.4	-9.3		37.6		
(between the source and the hall rear wall)								
@ 1/2 point	69.9	-9.2	37.4	-9.0		37.6		-9.0
@ 3/4 point	104.8	-6.2	37.4	-6.0		37.6		
@ mian floor rear wall	131.7	-3.6	37.4	-3.6				
@ 1st balcony rear wall	131.7	10.0						
@ hall rear wall	139.7					37.6	23.3	
(The hall rear wall is dertimined by the farest wall of the main floor at the central axis)								
@ w/ the max. width- m. floor								
@ w/ the max. width-balcony								
@ w/ the max. ceiling ht.-center								
@ end of main floor side wall	131.7		37.4					
@ end of balcony side wall	131.7					37.6		
average		-7.4	37.3	-7.3		37.5		
average (stage only)		-4.9	26.7	-4.9		26.7		

	p4 ceiling 1 coordinate (at y(p3)) z	p4 ceiling 1 coordinate |y|	p5 ceiling 1 coordinate (inside corner) |y|	p5 ceiling 1 coordinate (at y(p5)) z	p6 ceiling 2 coordinate (at y(p5)) z	p7 ceiling 2 coordinate (center) z	p8 s. penal half width |y|	p9 s. penal coordinate (center) z
@ stage rear wall	31.3	22.5				31.3		31.3
@ sound source	41.3	31.0				41.3		41.3
@ proscenium	48.0	34.6				48.0		48.0
@ 1/4 point	51.1	34.6				51.1		51.1
(between the source and the hall rear wall)								
@ 1/2 point	51.1	34.6				51.1		51.1
@ 3/4 point	51.1	34.6				51.1		51.1
@ hall rear wall	51.1	34.6				51.1		51.1
(The hall rear wall is dertimined by the farest wall of the main floor at the central axis)								
@ the place w/ the max. ceiling ht.								
average	49.9	34.6				49.9		49.9
average (stage only)	36.3	26.8				36.3		36.3
maximum room length	165.0							

Figure B-1. (Continued)

(B) Balcony details

		balcony face(b0)			underbalcony(b1)		
		x	y	z	x	y	z
1st	@ x axis	109.6	0.0	3.8	131.7	0.0	4.8
	@ side/transition	103.7	37.4				
	@ box/y axis	8.0	28.7	1.8	10.5	37.4	1.8
2nd	@ x axis	119.2	0.0	15.8	131.7	0.0	17.3
	@ side/transition	113.2	37.4				
	@ box/y axis	5.7	30.3	13.5	7.0	37.4	13.5
3rd	@ x axis						
	@ side/transition						
	@ box/y axis						

		balcony rear(b2)		
		x	y	z
1st	@ x axis	131.7	0.0	8.6
	@ side/transition			
	@ box/y axis	10.5	37.4	6.8
2nd	@ x axis	139.7	0.0	23.3
	@ side/transition			
	@ box/y axis	7.0	37.4	18.0
3rd	@ x axis			
	@ side/transition			
	@ box/y axis			

		sweep angle	balcony slope	balcony vert. angle	under blc. depth	under blc. height-op.	under blc. height-r	over blc. height	over blc. depth
1st	@ x axis	0.0	0.22	12.3	22.1	8.4	8.4	0.0	22.1
	@ side/transition	19.8							
	@ box/y axis	74.4	0.51	26.8	9.0	10.9	10.8	0.0	9.0
2nd	@ x axis	0.0	0.37	20.1	12.5	9.9	8.7	35.0	20.5
	@ side/transition	19.8							
	@ box/y axis	79.4	0.56	29.1	7.2	11.0	6.7	35.2	7.2
3rd	@ x axis								
	@ side/transition								
	@ box/y axis								

	main floor	balcony
Distance between two rows on the plan		
Distance between two seats on the plan		

Area in sqft. (including holes), Absorbent Surfaces and Diffusive Surfaces

(A1) Stage/speaking area

	floor/aidle	(G) % of absrobents and diffusion absorb. surfaces	zig-zag surfaces	coffered surfaces	convex surfaces	% of others
stage/orchestra	1655.3	0.0				
orchestra pit	0.0	0.0				

Figure B-1. (Continued)

(A2) Floors area--Audience area

		seating dianogal	aisle horz+vert or diagonal		absorb. surfaces (for floor/aisle only)	zig-zag surfaces	coffered surfaces	convex surfaces	others
	main floor	6241.6	3371.8		100.0	0.0			
	1st balcony	3165.5	649.5		100.0	100.0			
	2nd balcony	2722.2	1475.9		100.0	100.0			
	3rd balcony	0.0	0.0		0.0	0.0			
	total	12129.3	5497.2		100.0	38.7			
(B) walls area	pit/stage face		142.2	wall	0.0	0.0	0.0	0.0	0.0
	organ		922.5		0.0	0.0	0.0	0.0	100.0
	stage envelope		3727.5		0.0	0.0	37.0	0.0	0.0
	m floor and bal. rear		3389.1		0.0	0.0	0.0	0.0	0.0
	balcony face and side		1918.8		0.0	0.0	0.0	0.0	100.0
	others(side walls)		13358.8		0.0	0.0	0.0	0.0	67.8
(C) Ceiling area	main		14006.6	ceiling	0.0	0.0	100.0	0.0	0.0
	under balcony		6187.9	ceiling	0.0	0.0	0.0	0.0	0.0
(D) Suspended panels	over stage		1840.3	panel		0.0	100.0	0.0	0.0
(not including openin	over audience		0.0			0.0	0.0	0.0	0.0
Total opening among suspended panels			0.0						
				subtotal %		0.0	33.3	0.0	23.0
(E) total area excluding seats			51723.8	total %	10.6				56.3

(H) Dimension of diffusive surfaces

		df. surface	depth	period-h
Walls	organ	922.5	2.0	15.5
	stage envelope	1380.9	0.6	3.3
	m floor and bal. rear	0.0		
	balcony face and side	1918.8	0.3	19.3
	others	9063.1	2.2	19.3
	total	13285.3		

average depth	1.7
depth difference	1.9
average length of undulation	17.4
undulation difference	16.0
max panel size of aud. chamber	4.0
angler difference (Awp-Aw)	0.0

		df. surface	depth	period-l
Ceiling,lng	main	14006.6	1.4	19.3
(sus. p)	over stage	1840.3	3.6	10.6
(sus. p)	over audience	0.0		
	total	15846.9		

average depth	1.7
depth difference	2.2
average length of undulation	18.3
undulation difference	8.7
max panel size of aud. chamber	16.7
angler difference (Acp-Ac)	0.0

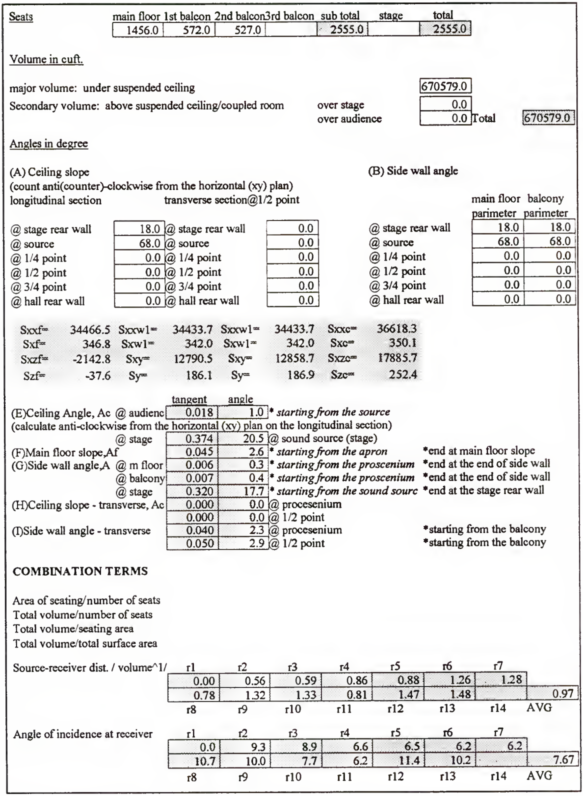
		df. surface	depth	period-t
Ceiling,trv	main	14006.6	1.4	19.3
(sus. p)	over stage	1840.3	3.6	26.7
(sus. p)	over audience	0.0		
	total	15846.9		

average depth	1.7
depth difference	2.2
average length of undulation	20.2
undulation difference	7.4

(G) Average absorption coefficient

		Major Surface	125 Hz	250 Hz	500 Hz	1 kHz	2 kHz	4 kHz
floor	stage floor	wood/with chairs	0.15	0.19	0.22	0.39	0.38	0.30
	audience seats	leather/wood-empty	0.44	0.54	0.60	0.62	0.58	0.50
	aud. fl. excluding seat	carpet at m.f. only	0.06	0.07	0.10	0.15	0.30	0.43
walls	pit/stage face	1" wood	0.19	0.14	0.09	0.06	0.06	0.05
	organ	organ	0.30	0.30	0.40	0.30	0.30	0.30
	stage envelope	1" wood	0.19	0.14	0.09	0.06	0.06	0.05
	m floor and bal. rear	38% pl on lath, 62% 1" p	0.06	0.05	0.04	0.04	0.04	0.04
	balcony face and side	38% pl on lath, 62% 1" p	0.06	0.05	0.04	0.04	0.04	0.04
	others	38% pl on lath, 62% 1" p	0.06	0.05	0.04	0.04	0.04	0.04
ceilings	main	3/4" p on metal scresn	0.14	0.10	0.06	0.05	0.04	0.03
	under balcony	3/4" p on metal scresn	0.14	0.10	0.06	0.05	0.04	0.03
sus panels	over stage	1" wood	0.19	0.14	0.09	0.06	0.06	0.05
	over audience							
			0.176	0.177	0.171	0.177	0.180	0.170
	total sabine		11234.15	11302.59	10943.12	11321.00	11486.17	10866.48
	estimated T60-totlal v (for 50 % RH)		2.92	2.91	3.00	2.76	2.45	2.08
	estimated T60-major v		2.92	2.91	3.00	2.76	2.45	2.08

Figure B-1. (Continued)



Seats	main floor	1st balcon	2nd balcon	3rd balcon	sub total	stage	total
	1456.0	572.0	527.0		2555.0		2555.0

Volume in cuft.

major volume: under suspended ceiling		670579.0		
Secondary volume: above suspended ceiling/coupled room	over stage	0.0		
	over audience	0.0	Total	670579.0

Angles in degree

(A) Ceiling slope

(count anti(counter)-clockwise from the horizontal (xy) plan)

(B) Side wall angle

longitudinal section		transverse section@1/2 point			main floor parimeter	balcony parimeter
@ stage rear wall	18.0	@ stage rear wall	0.0	@ stage rear wall	18.0	18.0
@ source	68.0	@ source	0.0	@ source	68.0	68.0
@ 1/4 point	0.0	@ 1/4 point	0.0	@ 1/4 point	0.0	0.0
@ 1/2 point	0.0	@ 1/2 point	0.0	@ 1/2 point	0.0	0.0
@ 3/4 point	0.0	@ 3/4 point	0.0	@ 3/4 point	0.0	0.0
@ hall rear wall	0.0	@ hall rear wall	0.0	@ hall rear wall	0.0	0.0

Sxxf=	34466.5	Sxxw1=	34433.7	Sxxw1=	34433.7	Sxxc=	36618.3
Sxf=	346.8	Sxw1=	342.0	Sxw1=	342.0	Sxc=	350.1
Sxzf=	-2142.8	Sxy=	12790.5	Sxy=	12858.7	Sxzc=	17885.7
Szf=	-37.6	Sy=	186.1	Sy=	186.9	Szc=	252.4

		tangent	angle		
(E)Ceiling Angle, Ac	@ audienc	0.018	1.0	* *starting from the source*	

(calculate anti-clockwise from the horizontal (xy) plan on the longitudinal section)

		tangent	angle		
	@ stage	0.374	20.5	@ sound source (stage)	
(F)Main floor slope,Af		0.045	2.6	* *starting from the apron*	*end at main floor slope
(G)Side wall angle,A	@ m floor	0.006	0.3	* *starting from the proscenium*	*end at the end of side wall
	@ balcony	0.007	0.4	* *starting from the proscenium*	*end at the end of side wall
	@ stage	0.320	17.7	* *starting from the sound sourc*	*end at the stage rear wall
(H)Ceiling slope - transverse, Ac		0.000	0.0	@ procesenium	
		0.000	0.0	@ 1/2 point	
(I)Side wall angle - transverse		0.040	2.3	@ procesenium	*starting from the balcony
		0.050	2.9	@ 1/2 point	*starting from the balcony

COMBINATION TERMS

Area of seating/number of seats
Total volume/number of seats
Total volume/seating area
Total volume/total surface area

Source-receiver dist. / volume^1/	r1	r2	r3	r4	r5	r6	r7	
	0.00	0.56	0.59	0.86	0.88	1.26	1.28	
	0.78	1.32	1.33	0.81	1.47	1.48		0.97
	r8	r9	r10	r11	r12	r13	r14	AVG

Angle of incidence at receiver	r1	r2	r3	r4	r5	r6	r7	
	0.0	9.3	8.9	6.6	6.5	6.2	6.2	
	10.7	10.0	7.7	6.2	11.4	10.2		7.67
	r8	r9	r10	r11	r12	r13	r14	AVG

Figure B-1. (Continued)

APPENDIX C

ARCHITECTURAL DATA AND ACOUSTICAL DATA OF THE HALLS

Table C-1 summarizes data of the hall averages and standard deviations of acoustical measures taken in the 22 halls. Table C-2 summarizes data of room architectural parameters measured in the 22 halls. Simple statistics was attached including the maximum, minimum, and average of each variable.

Table C-1. Data of the hall averages and standard deviations of acoustical measures taken in the 22 halls.

	avg(EDT) sec.	avg(C80 dB	avg(G) dB	avg(BR)	avg(TR)	avg(IACC)	std(EDT) sec.	std(C80) dB	std(G) dB	std(BR)	std(TR)	std(IACC)
O1	2.10	-0.99	3.17	1.016	0.884	0.488	0.153	1.066	1.380	0.026	0.016	0.103
O2	2.36	-2.29	4.66	0.894	0.993	0.23	0.168	1.145	1.195	0.041	0.022	0.088
O3	1.30	3.64	2.89	1.221	0.852	0.34	0.128	0.944	2.151	0.082	0.037	0.071
O4	1.65	0.63	2.07	1.075	0.936	0.241	0.110	0.870	1.770	0.062	0.021	0.056
O5	1.69	0.13	1.25	0.982	0.938	0.212	0.112	0.641	1.921	0.052	0.046	0.053
O6	1.17	2.11	0.75	0.955	0.953	0.299	0.104	1.472	2.690	0.069	0.029	0.120
O7	1.55	0.87	2.51	0.994	0.951	0.294	0.132	1.260	2.361	0.067	0.038	0.083
O8	2.21	-0.64	8.39	1.055	0.895	0.287	0.184	1.218	1.562	0.032	0.025	0.081
M1	1.99	-0.08	2.20	1.059	0.880	0.634	0.156	0.720	2.521	0.051	0.028	0.076
M2	1.11	3.04	2.78	1.151	0.971	0.394	0.139	1.519	1.871	0.070	0.029	0.118
M3	2.08	-1.33	4.93	1.089	0.902	0.479	0.068	0.530	0.766	0.032	0.015	0.020
C1	1.35	1.73	9.45	0.826	0.992	0.362	0.023	0.039	1.152	0.038	0.006	0.015
C2	1.06	3.44	5.78	1.107	0.932	0.338	0.103	1.043	1.599	0.085	0.010	0.068
C3	1.40	0.85	10.44	1.073	0.896	0.252	0.104	0.468	1.445	0.017	0.047	0.070
L1	0.48	9.77	10.79	1.161	1.061		0.057	1.085	1.295	0.006	0.020	
L2	1.08	2.99	19.90	0.809	0.945		0.033	0.140	0.041	0.009	0.023	
L3	1.23	1.89	19.87	0.787	0.988		0.040	0.628	0.513	0.029	0.013	
L4	2.29	-1.59	11.40	1.026	0.974	0.384	0.071	0.707	1.187	0.042	0.011	0.135
L5	1.06	2.85	10.01	1.011	0.875	0.327	0.016	0.458	1.258	0.070	0.022	0.134
L6	1.79	0.00	14.00	0.864	1.024	0.187	0.049	0.795	0.676	0.023	0.006	0.083
L7	2.03	-1.14	10.62	1.043	0.878	0.341	0.092	0.477	1.104	0.038	0.029	0.128
L8	0.64	7.84	9.56	1.253	0.969		0.113	1.117	1.190	0.110	0.119	
Max	2.36	9.77	19.90	1.253	1.061	0.634	0.18	1.52	2.69	0.110	0.119	0.135
Min	0.48	-2.29	0.75	0.787	0.852	0.187	0.02	0.04	0.04	0.006	0.006	0.015
Avg	1.53	1.53	7.61	1.020	0.940	0.339	0.10	0.83	1.44	0.048	0.028	0.083

Table C-2. Data of room architectural parameters measured in the 22 halls.

	V cu.ft.	Sa sq.ft.	n	N seat	V/Sa	Sb/Sa	Sa/N	Sb/n	Ss/Sa	W ft.	H ft.
O1	756,558	18,209	2	2,535	47.2	0.580	7.2	4655	0.135	84.4	55.5
O2	670,579	13,785	2	2,909	55.3	0.485	4.7	2944	0.136	74.8	55.6
O3	644,000	20,310	1	2,909	35.6	0.512	7.0	9266	0.122	127.2	37.4
O4	577,676	13,975	2	2,108	46.8	0.493	6.6	3040	0.132	77.5	42.0
O5	763,501	20,064	3	2,829	43.8	0.517	7.1	3005	0.151	92.5	54.6
O6	554,861	16,905	3	2,984	37.4	0.631	5.7	3120	0.140	67.4	67.0
O7	554,000	14,424	1	2,066	46.2	0.648	7.0	7759	0.204	88.9	44.8
O8	399,778	6,321	1	1,167	79.6	0.268	5.4	1345	0.258	69.3	56.1
M1	764,611	20,813	3	2,563	41.2	0.581	8.1	3596	0.120	97.2	64.3
M2	378,866	14,312	1	2,050	28.7	0.538	7.0	7107	0.084	78.4	43.8
M3	516,782	14,973	0	2,269	39.6	0.000	6.6	0	0.148	119.8	33.9
C1	119,339	3,462	1	490	53.7	0.222	7.1	493	0.559	43.6	28.9
C2	75,921	3,885	1	620	22.4	0.498	6.3	1685	0.147	59.3	22.4
C3	100,099	4,478	1	757	27.4	0.387	5.9	1411	0.228	86.3	23.7
L1	14,109	810	0	100	17.4	0.000	8.1	0	0.247	25.0	11.1
L2	6,775	654	0	54	10.4	0.000	12.1	0	0.209	28.0	8.5
L3	9,327	667	0	54	14.0	0.000	12.4	0	0.186	28.0	11.6
L4	147,032	5,146	0	640	28.6	0.000	8.0	0	0.066	85.8	17.1
L5	48,325	2,024	0	306	23.9	0.000	6.6	0	0.304	52.2	17.2
L6	21,000	923	0	123	22.8	0.000	7.5	0	0.152	31.6	15.1
L7	57,920	1,917	0	302	30.2	0.000	6.3	0	0.148	72.2	14.9
L8	30,236	1,543	0	173	19.6	0.000	8.9	0	0.079	44.4	12.3
Max	764,611	20,813	3	2,984	79.56	0.65	12.35	9,266	0.56	127.16	66.99
Min	6,775	654	0	54	10.36	0.00	4.74	0	0.07	25.00	8.50
Avg	327,786	9,073	1	1,364	35.08	0.29	7.35	2,247	0.18	69.71	33.54

	L/Lmax	Lmax ft.	Ws ft.	Hs ft.	Ls ft.	Hsr/Hs	H/W	HW	HW/Lmax	Lmax/W	Hs/H
O1	0.899	129.0	60.9	27.8	36.0	1.356	0.657	4684.9	36.3	1.53	0.501
O2	0.943	139.7	53.4	41.2	26.8	1.000	0.744	4161.3	29.8	1.87	0.741
O3	0.788	137.0	65.6	27.3	34.7	1.000	0.295	4762.0	34.8	1.08	0.729
O4	0.678	140.8	45.6	21.8	35.8	1.000	0.543	3256.3	23.1	1.82	0.519
O5	0.958	137.2	64.6	50.3	33.3	1.000	0.591	5054.3	36.8	1.48	0.920
O6	0.732	112.0	49.0	21.1	36.0	1.000	0.994	4516.1	40.3	1.66	0.315
O7	0.709	127.0	49.0	30.9	40.5	1.000	0.504	3985.4	31.4	1.43	0.690
O8	0.890	90.1	61.6	14.7	21.3	3.789	0.809	3886.1	43.1	1.30	0.262
M1	0.828	120.0	81.0	46.7	15.5	1.715	0.661	6246.5	52.1	1.23	0.727
M2	0.837	113.2	45.2	61.3	30.7	1.000	0.558	3431.0	30.3	1.44	1.401
M3	1.000	127.0	48.2	23.7	36.0	1.000	0.283	4055.2	31.9	1.06	0.700
C1	0.783	85.2	28.0	32.7	26.8	1.000	0.663	1258.6	14.8	1.96	1.132
C2	1.000	52.0	52.8	10.7	10.0	1.000	0.377	1324.4	25.5	0.88	0.479
C3	0.774	54.0	32.4	20.5	17.8	1.000	0.275	2045.9	37.9	0.63	0.864
L1	1.000	43.7	25.0	11.4	4.8	1.000	0.444	277.5	6.4	1.75	1.027
L2	1.000	24.0	29.0	8.5	5.0	1.000	0.304	238.0	9.9	0.86	1.000
L3	1.000	24.0	29.0	11.6	5.3	1.000	0.414	324.8	13.5	0.86	1.000
L4	1.000	92.0	54.6	14.2	7.0	1.000	0.199	1467.2	15.9	1.07	0.830
L5	1.000	54.0	45.0	20.3	5.5	1.000	0.330	897.8	16.6	1.03	1.180
L6	1.000	38.8	24.2	13.3	4.5	1.000	0.478	477.2	12.3	1.23	0.881
L7	1.000	48.0	40.0	26.8	7.0	1.000	0.206	1075.8	22.4	0.66	1.799
L8	1.000	41.2	33.4	12.5	9.0	1.000	0.277	546.1	13.3	0.93	1.016
Max	1.00	140.80	81.00	61.30	40.50	3.79	0.99	6246.5	52.05	1.96	1.80
Min	0.68	24.00	24.20	8.50	4.50	1.00	0.20	238.0	6.35	0.63	0.26
Avg	0.90	87.72	46.25	24.97	20.42	1.18	0.48	2635.1	26.29	1.26	0.85

Table C-2. (Continued).

	Ws/W	Hs/Ws	Ls/Ws	Ls/L	HsWs	HsWs/HW	Aw degree	Ac degree	Af degree	Asw degree	Asc degree
O1	0.721	0.456	0.591	0.279	1693.0	0.361	-4.19	4.10	3.70	24.20	15.50
O2	0.714	0.772	0.502	0.192	2200.1	0.529	0.35	1.00	2.60	17.70	20.50
O3	0.516	0.416	0.529	0.253	1790.9	0.376	15.34	3.00	5.00	24.20	28.70
O4	0.589	0.478	0.785	0.254	994.1	0.305	8.45	6.10	4.50	6.40	3.20
O5	0.698	0.779	0.515	0.243	3249.4	0.643	0.70	3.10	4.40	33.60	5.50
O6	0.727	0.431	0.735	0.321	1033.9	0.229	-0.81	4.90	2.80	4.80	14.90
O7	0.551	0.631	0.827	0.319	1514.1	0.380	9.37	8.40	2.40	12.50	11.40
O8	0.889	0.239	0.346	0.236	905.5	0.233	0.00	-2.00	4.60	48.60	36.70
M1	0.833	0.577	0.191	0.129	3782.7	0.606	-5.61	-6.10	6.90	20.50	18.90
M2	0.577	1.356	0.679	0.271	2770.8	0.808	11.07	12.30	2.70	0.00	0.00
M3	0.402	0.492	0.747	0.283	1142.3	0.282	31.20	0.40	11.30	18.80	25.40
C1	0.643	1.168	0.957	0.315	915.6	0.727	-1.88	0.00	0.00	0.00	0.00
C2	0.891	0.203	0.189	0.192	565.0	0.427	-33.71	-21.60	0.00	51.50	0.00
C3	0.376	0.633	0.549	0.330	664.2	0.325	19.32	9.00	0.00	46.90	0.00
L1	1.000	0.456	0.192	0.110	285.0	1.027	0.00	0.00	4.80	0.00	0.00
L2	1.036	0.293	0.172	0.208	246.5	1.036	0.00	0.00	0.00	0.00	0.00
L3	1.036	0.400	0.183	0.221	336.4	1.036	-7.40	0.00	0.00	0.00	0.00
L4	0.636	0.260	0.128	0.076	775.3	0.528	8.30	1.10	5.50	58.00	18.20
L5	0.862	0.451	0.122	0.102	913.5	1.017	10.20	0.00	8.30	0.00	0.00
L6	0.766	0.550	0.186	0.116	321.9	0.675	6.30	-3.00	3.40	14.90	12.50
L7	0.554	0.670	0.175	0.146	1072.0	0.996	50.50	-2.90	5.40	53.60	10.50
L8	0.752	0.374	0.269	0.218	417.5	0.764	3.30	0.00	4.70	33.50	0.00
Max	1.04	1.36	0.96	0.33	3782.7	1.04	50.50	12.30	11.30	58.00	36.70
Min	0.38	0.20	0.12	0.08	246.5	0.23	-33.71	-21.60	0.00	0.00	0.00
Avg	0.72	0.55	0.44	0.22	1254.1	0.60	5.49	0.81	3.77	21.35	10.09

	Awp degree	Acp degree	Act degree	Acpt degree	X ft.	|Y| ft.	Z ft.	R ft.	A degree	|AH| degree	RC ft.
O1	-4.19	4.10	0.00	0.00	79.32	19.04	7.32	84.63	7.84	15.30	37.49
O2	0.35	1.00	0.00	0.00	87.78	19.71	6.08	92.09	8.33	14.51	34.48
O3	19.34	5.00	-3.60	-3.60	78.88	25.08	8.60	85.74	8.65	18.40	23.02
O4	8.45	0.00	0.00	0.00	74.14	18.51	16.71	80.71	5.41	16.34	32.68
O5	0.70	3.10	0.00	0.00	82.12	16.31	7.20	86.70	6.18	13.83	38.71
O6	0.00	0.00	7.80	7.80	70.67	19.17	14.60	77.93	8.77	16.89	22.89
O7	9.37	12.40	6.40	6.40	68.19	18.65	17.69	75.63	5.99	17.83	28.35
O8	0.00	0.00	4.40	4.40	57.27	11.33	3.21	60.42	9.97	13.18	48.96
M1	-24.11	0.00	21.70	0.00	66.88	27.11	17.92	80.70	6.57	25.78	26.09
M2	11.07	12.30	0.00	0.00	65.63	18.89	13.25	72.94	6.80	17.24	22.22
M3	31.20	0.40	4.30	4.30	77.32	27.90	6.77	84.27	10.67	20.03	29.75
C1	-1.88	0.00	19.40	19.40	53.90	3.90	1.95	54.40	8.90	5.00	24.80
C2	0.00	0.00	15.20	6.24	24.54	18.00	0.26	33.90	6.10	35.28	12.60
C3	19.32	0.00	12.30	12.30	32.04	19.20	0.64	40.08	6.16	30.32	17.30
L1	0.00	0.00	0.00	0.00	28.55	1.50	-1.10	28.60	7.60	3.15	6.95
L2	0.00	0.00	0.00	0.00	13.00	5.00	-1.80	14.10	8.90	19.00	4.80
L3	0.00	0.00	0.00	0.00	13.50	5.00	-1.80	15.25	8.80	18.40	7.90
L4	8.30	1.10	0.00	0.00	52.83	18.00	0.20	57.87	7.25	19.97	14.33
L5	10.20	0.00	0.00	0.00	35.50	10.17	2.20	37.63	5.77	15.90	8.60
L6	6.30	-3.00	0.00	0.00	23.03	5.20	-2.27	24.00	11.17	12.30	11.27
L7	50.50	-2.90	7.80	0.00	22.95	14.60	-0.65	29.35	5.90	31.40	12.53
L8	3.30	0.00	0.00	0.00	25.13	8.70	-0.70	26.97	6.13	18.90	8.30

Table C-2. (Continued).

	std(x) ft.	std(|y|) ft.	std(z) ft.	std(r) ft.	std(a) degree	std(|ah|) degree	std(rc) ft.	æ	BR(alpha)	TR(alpha)	Kch
O1	27.92	13.72	15.69	27.74	2.61	12.90	22.73	0.181	1.27	0.85	0
O2	29.96	12.01	11.08	28.45	1.89	10.72	19.65	0.174	0.99	0.99	0
O3	26.86	17.63	13.45	28.04	0.89	12.70	14.78	0.237	1.43	0.92	0
O4	28.89	10.27	19.05	30.16	2.90	11.77	18.58	0.190	1.28	0.85	0
O5	33.07	12.61	14.72	31.82	3.32	13.18	21.83	0.206	1.26	0.96	0
O6	21.89	11.48	19.13	21.79	1.74	11.10	23.34	0.256	1.20	0.98	0
O7	29.20	11.72	18.75	30.51	2.94	13.87	19.20	0.193	1.22	1.08	0
O8	20.41	10.06	10.84	20.08	1.75	12.79	11.12	0.181	0.98	1.16	0
M1	27.95	16.45	17.93	25.01	2.66	19.79	24.00	0.180	1.30	0.95	0
M2	25.26	14.78	19.20	27.26	2.50	13.28	14.57	0.211	1.30	0.86	0
M3	20.58	17.66	5.57	21.48	1.26	11.58	7.20	0.217	1.38	0.97	0
C1	19.30	0.60	5.95	19.30	2.30	2.40	5.30	0.154	0.92	0.91	0
C2	10.18	12.21	5.09	7.55	2.73	24.21	9.22	0.185	1.52	0.82	0
C3	10.03	12.20	5.93	8.73	2.01	19.45	9.01	0.115	0.95	0.65	0
L1	6.75	0.00	0.40	6.70	1.40	0.75	0.55	0.279	1.85	0.84	1
L2	5.00	3.00	0.00	5.70	3.60	5.00	0.00	0.149	0.98	0.82	1
L3	5.50	3.00	0.00	5.35	3.70	4.40	0.00	0.138	1.06	0.85	1
L4	19.16	12.50	4.22	17.68	1.62	15.27	2.88	0.133	0.87	0.67	1
L5	8.44	6.98	1.22	8.51	1.23	10.37	1.22	0.213	1.42	0.87	0
L6	5.97	3.67	0.65	6.01	0.34	8.06	1.48	0.166	1.39	1.13	1
L7	8.18	10.59	1.05	8.46	1.10	20.67	0.38	0.123	1.03	0.60	1
L8	8.73	5.30	1.56	9.37	1.59	10.49	1.56	0.378	1.39	0.97	1
Max	33.07	17.66	19.20	31.82	3.70	24.21	24.00	0.38	1.85	1.16	1.00
Min	5.00	0.00	0.00	5.35	0.34	0.75	0.00	0.12	0.87	0.60	0.00
Avg	18.15	9.93	8.70	17.99	2.10	12.03	10.39	0.19	1.23	0.90	0.32

	Dob ft.	Dub ft.	Hub ft.	Dub/Hub	Aub degree	Hub/H	Dub/Lmax	Db/Lmax	Dsb ft.	Dsb/Hsb	Ksb
O1	27.40	21.90	18.45	1.187	17.853	0.332	0.189	0.191	4.20	0.486	1
O2	21.30	17.30	9.15	1.891	1.987	0.164	0.131	0.138	8.10	0.740	1
O3	63.00	34.00	18.40	1.848	5.713	0.491	0.315	0.354	0.00	0.000	1
O4	51.10	28.45	11.05	2.575	3.421	0.263	0.298	0.282	7.80	0.729	1
O5	16.53	14.60	12.60	1.159	17.139	0.231	0.111	0.113	9.10	0.722	1
O6	24.50	18.00	9.48	1.900	9.854	0.141	0.220	0.190	9.15	0.943	1
O7	40.00	21.90	10.60	2.066	6.645	0.237	0.243	0.244	23.05	2.305	1
O8	16.65	11.65	12.25	0.951	12.587	0.218	0.145	0.157	0.00	0.000	0
M1	24.53	17.87	11.57	1.545	14.946	0.180	0.180	0.177	8.67	0.716	1
M2	70.70	51.20	18.00	2.844	8.119	0.411	0.541	0.538	0.00	0.000	0
M3	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
C1	18.90	0.40	9.70	0.041	0.000	0.336	0.006	0.113	0.00	0.000	0
C2	24.30	24.30	7.80	3.115	0.000	0.349	0.467	0.467	0.00	0.000	0
C3	14.00	0.70	8.70	0.080	29.760	0.367	0.017	0.136	20.00	2.299	1
L1	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
L2	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
L3	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
L4	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
L5	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
L6	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
L7	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0
L8	0.00	0.00				1.000	0.000	0.000	0.00	0.000	0

Table C-2. (Continued).

	Pwd %	Pcdl %	Pcdt %	Dwd ft.	Dcdl ft.	Dcdt ft.	Lwd ft.	Lcdl ft.	Lcdt ft.	Lmwp ft.	Lmcp ft.
O1	85	100	100	1.70	3.00	3.00	11.10	14.00	14.00	0.00	7.00
O2	57	100	100	1.70	1.70	1.70	17.40	18.30	20.20	4.00	16.70
O3	84	100	0	1.10	0.90	0.00	13.50	22.70		12.00	22.70
O4	45	100	0	3.30	4.10	0.00	14.80	30.10		9.00	34.00
O5	100	100	100	1.80	1.00	1.00	21.80	14.00	14.00	7.40	4.00
O6	26	21	6	7.20	4.00	9.00	11.80	18.80	31.00	8.50	16.50
O7	42	69	0	3.60	0.70	0.00	6.70	9.10		6.40	9.80
O8	71	20	37	2.50	4.00	4.60	20.00	8.80	9.60	5.40	0.00
M1	70	64	64	3.80	3.10	3.10	14.80	16.20	13.00	16.20	16.80
M2	58	84	84	1.30	4.00	4.00	7.70	18.20	18.20	3.00	9.80
M3	100	100	100	4.90	1.00	1.00	31.10	9.00	15.00	0.00	0.00
C1	60	100	100	5.20	1.80	6.20	13.50	13.80	20.20	9.80	11.60
C2	78	96	96	5.90	8.00	8.20	9.80	17.60	18.60	1.30	16.00
C3	8	7	94	4.00	8.25	2.90	19.30	18.05	19.00	18.00	14.00
L1	0	100	0	0.00	1.30	0.00		2.80			2.30
L2	17	0	0	2.80	0.00	0.00	6.60			5.80	
L3	14	100	100	2.40	3.10	3.10	6.30	9.80	9.80	6.00	8.60
L4	0	100	19	0.00	1.20	3.67		18.50	7.48		18.25
L5	47	100	100	0.30	0.70	0.70	6.80	6.80	19.30	4.70	5.60
L6	5	0	0	2.00	0.00	0.00	2.50			2.50	
L7	0	0	11	0.00	0.00	3.80			15.40		
L8	2	0	0	8.30	0.00	0.00	4.40		0.00	4.40	
Max	100	100	100	8.30	8.25	9.00	31.10	30.10	31.00	18.00	34.00
Min	0	0	0	0.00	0.00	0.00	2.50	2.80	0.00	0.00	0.00
Avg	44	66	51	2.90	2.36	2.54	12.63	14.81	15.30	6.55	11.87

	RTs sec.	C80_edt dB	G_edt dB	C80_rt dB	G_rt dB
O1	2.56	-2.11	4.90	-3.17	5.76
O2	2.88	-2.75	5.94	-3.79	6.81
O3	2.05	0.67	3.53	-1.98	5.49
O4	2.49	-0.75	5.02	-3.04	6.82
O5	2.32	-0.89	3.92	-2.66	5.30
O6	1.96	1.36	3.70	-1.74	5.96
O7	2.56	-0.38	4.93	-3.18	7.12
O8	2.90	-2.40	7.90	-3.82	9.07
M1	2.30	-1.81	4.62	-2.61	5.26
M2	1.57	1.69	5.14	-0.46	6.64
M3	2.17	-2.08	6.53	-2.30	6.71
C1	1.54	0.42	11.02	-0.36	11.58
C2	1.16	1.96	11.94	1.42	12.30
C3	1.78	0.19	11.94	-1.19	12.96
L1	0.47	8.56	15.78	8.74	15.70
L2	0.88	1.86	22.50	3.33	21.59
L3	1.14	1.01	21.68	1.53	21.33
L4	2.39	-2.59	12.40	-2.81	12.58
L5	1.03	2.00	13.88	2.18	13.76
L6	1.25	-1.22	19.77	0.94	18.21
L7	2.24	-1.93	15.92	-2.46	16.34
L8	0.38	5.84	13.72	11.16	11.47

APPENDIX D

ARCHITECTURAL DATA AND ACOUSTICAL DATA OF THE RECEIVER LOCATIONS

Table D-1 summarizes the terms of typical receiver locations used in the rooms. The terms described the relative locations of receivers in the rooms. Table D-2 summarizes data of acoustical measures for all receiver locations in the 22 halls. Table D-3 summarizes data of receiver architectural parameters for all receiver locations in the 22 halls. Simple statistics was attached including the maximum, minimum, and average of each variable.

Table D-1. Typical receiver locations used in the rooms.

CFM	Center Front of Main-floor
SFM	Side Front of Main-floor
CMM	Center Middle of Main-floor
SMM	Side Front of Main-floor
CRM	Center Rear of Main-floor
MRM	Middle Rear of Main-floor
SRM	Side Rear of Main-floor
CFB	Center Front of Balcony
SFB	Side Front of Balcony
CMB	Center Middle of Balcony
SMB	Side Front of Balcony
CRB	Center Rear of Balcony
MRB	Middle Rear of Balcony
SRB	Side Rear of Balcony
C1B	Center of 1st Balcony
M1B	Middle of 1st Balcony
S1B	Side of 1st Balcony
C2B	Center of 2nd Balcony
M2B	Middle of 2nd Balcony
S2B	Side of 2nd Balcony
C3B	Center of 3rd Balcony
M3B	Middle of 3rd Balcony
S3B	Side of 3rd Balcony
CX	Center of Side Box
SX	Side of Side Box

Table D-2. Data of acoustical measures for all receiver locations.

Room	Receiver	EDT10 sec.	C80 dB	G dB	BR(EDT)	TR(EDT)	IACC80
O1	CFM	1.73	0.68	4.49	0.976	0.890	0.665
	SFM	1.97	0.47	5.99	1.000	0.868	0.365
	CMM	2.23	-2.26	3.45	1.023	0.872	0.575
	SMM	2.25	-2.51	3.56	0.995	0.875	0.470
	CRM	2.16	-0.86	2.77	1.061	0.881	0.375
	SRM	2.19	-1.98	2.66	1.021	0.881	0.425
	C1B	2.07	-1.08	1.03	1.053	0.916	0.540
	S1B	2.13	-1.00	2.89	1.017	0.904	
	C2B	2.15	-0.38	1.71	0.997	0.865	
O2	CFM	2.13	-0.67	7.14	0.957	0.963	0.205
	SFM	2.09	0.00	6.27	0.906	0.966	
	CMM	2.41	-3.08	5.55	0.932	0.969	
	SMM	2.33	-1.79	4.89	0.932	0.995	0.114
	CRM	2.16	-1.61	4.23	0.827	1.016	0.168
	SRM	2.26	-2.25	3.02	0.905	0.967	
	B1B	2.43	-2.51	5.39	0.903	1.006	
	S1B	2.36	-1.94	3.92	0.882	1.011	0.238
	C1B	2.40	-2.77	3.72	0.805	1.006	
	B2B	2.63	-4.33	4.78	0.902	0.982	
	S2B	2.48	-2.96	3.55	0.886	1.027	
	C2B	2.61	-3.52	3.46	0.889	1.007	0.388
O3	CFM	1.18	5.88	7.14	1.199	0.848	0.452
	SFM	1.38	3.99	5.70	1.172	0.871	
	CMM	1.43	3.09	4.63	1.180	0.827	
	SMM	1.49	2.13	3.72	1.159	0.819	0.302
	CRM	1.31	3.96	3.70	1.223	0.846	0.262
	SRM	1.34	3.15	3.23	1.152	0.854	
	FSRM	1.44	2.32	0.25	1.160	0.813	0.266
	CFB	1.24	4.38	2.52	1.105	0.856	0.374
	SFB	1.17	3.78	2.01	1.374	0.887	
	CRB	1.38	3.19	-0.37	1.281	0.837	
	SRB	1.16	3.86	1.23	1.357	0.816	0.399
	FSRB	1.07	3.97	0.94	1.290	0.952	
O4	CFM	1.50	1.96	5.51	1.017	0.961	0.313
	SFM	1.53	1.38	4.30	1.031	0.912	
	CMM	1.58	1.36	1.53	1.084	0.916	
	SMM	1.63	0.93	0.31	1.059	0.907	0.311
	CRM	1.49	1.30	-0.52	1.145	0.917	0.169
	SRM	1.51	1.96	-1.16	1.251	0.941	
	CX	1.64	0.31	0.47	1.108	0.900	
	SX	1.77	-0.07	3.24	1.022	0.942	0.269
	CFB	1.70	-0.11	2.40	1.082	0.953	0.166
	SFB	1.81	-0.64	1.94	1.073	0.952	
	CMB	1.72	0.04	2.66	1.019	0.976	
	SMB	1.81	-0.87	2.06	1.080	0.944	0.220
	CRB	1.73	0.46	3.18	0.999	0.938	0.236
	SRB	1.63	0.80	3.02	1.077	0.938	
O5	CFM	1.45	1.13	4.64	0.940	0.956	0.261
	SFM	1.65	0.96	3.18	0.960	0.957	
	CMM	1.59	0.30	1.49	0.953	0.997	
	SMM	1.75	-0.02	1.38	0.966	0.979	0.250
	CRM	1.75	-0.45	3.55	1.095	0.934	0.121
	SRM	1.85	-0.81	2.50	0.998	0.940	
	CUB	1.72	0.28	1.18	1.079	0.931	
	SUB	1.76	0.02	-0.44	0.973	0.825	0.157
	C1B	1.71	0.21	-1.07	0.932	0.871	0.248
	C2B	1.65	0.32	-2.23	0.996	0.950	
	S2B	1.81	-1.09	0.84	0.961	0.932	0.233
	C3B	1.54	0.77	0.00	0.925	0.986	
O6	CFM	1.02	4.40	6.15	1.079	0.964	0.481
	SFM	1.13	4.05	5.47	0.964	0.931	
	CMM	1.23	0.86	2.44	0.948	0.972	
	SMM	1.21	2.07	0.96	0.870	0.941	0.163
	CRM	1.17	1.81	-1.28	0.910	1.005	0.254
	SRM	1.12	2.75	-0.74	0.875	1.005	
	C1B	1.07	3.01	0.91	1.104	0.898	0.429
	S1B	1.31	0.11	1.05	0.971	0.932	
	C2B	1.01	3.16	-0.03	0.908	0.952	
	S2B	1.25	0.07	-0.61	0.957	0.943	0.176
	C3B	1.11	2.91	-2.43	0.914	0.946	0.290
	S3B	1.35	0.06	-2.93	0.954	0.943	
O7	CFM	1.36	2.00	6.35	1.046	1.036	0.190
	SFM	1.58	1.59	4.18	0.953	0.940	
	CRM	1.47	1.62	5.83	1.064	0.917	
	SRM	1.33	3.77	5.15	1.122	0.918	0.393
	CX	1.35	1.58	3.69	0.892	0.958	
	SX	1.70	0.47	1.97	0.954	0.928	
	CFB	1.65	-0.30	2.19	1.022	0.906	0.299
	SFB	1.72	-0.73	0.49	0.943	0.981	
	CMB	1.66	-0.78	0.85	1.060	0.965	

Table D-2. (Continued).

Room	Receiver	EDT10 sec.	C80 dB	G dB	BR(EDT)	TR(EDT)	IACC80
	SMB	1.62	-0.04	0.50	0.985	0.950	
	CRB	1.56	0.48	-0.45	0.908	1.003	
	SRB	1.54	0.80	-0.65	0.980	0.909	
O8	CFM	1.93	0.53	10.64	1.064	0.863	0.318
	SFM	2.08	-0.24	9.30	1.045	0.883	
	CMM	2.21	-0.66	9.26	1.099	0.868	
	SMM	2.30	-1.29	8.88	1.006	0.906	0.272
	CRM	2.00	1.37	6.83	1.097	0.875	0.166
	SRM	2.10	0.47	8.58	1.042	0.886	
	C1B	2.45	-2.58	5.93	1.076	0.925	0.391
	S1B	2.47	-1.97	6.27	1.006	0.902	
	C2B	2.35	-1.37	9.82	1.056	0.944	
M1	CMF	1.69	1.09	6.24	1.061	0.842	0.687
	SMF	1.88	0.68	2.43	1.062	0.837	
	RMF	1.85	0.49	5.38	1.070	0.866	0.703
	C1B	1.96	0.37	0.30	1.030	0.877	0.634
	M1B	2.14	-0.62	1.39	1.009	0.891	
	S1B	1.96	-0.39	4.71	1.083	0.883	
	B3C	2.05	-0.38	-1.27	1.067	0.895	0.510
	M3B	2.08	-0.68	-0.40	1.172	0.932	
	F3B	2.24	-1.25	1.06	0.981	0.897	
M2	CFM	0.98	5.07	7.10	1.092	0.977	0.517
	SFM	1.18	3.05	4.41	1.100	0.974	
	CMM	1.00	4.28	2.64	1.159	0.934	
	SMM	1.14	2.84	3.16	1.180	0.959	0.460
	CRM	0.89	4.93	2.14	1.132	1.039	0.515
	SRM	0.91	5.38	0.25	1.318	0.999	
	CFB	1.20	2.16	4.38	1.222	0.931	0.402
	SFB	1.30	1.34	3.06	1.159	0.963	
	CMB	1.16	2.05	2.81	1.039	0.974	
	SMB	1.31	1.18	2.08	1.192	0.945	0.245
	CRB	1.01	3.37	1.57	1.136	0.999	0.227
	SRB	1.22	0.87	-0.24	1.087	0.960	
M3	CFM	2.03	-0.98	5.60	1.144	0.900	0.482
	SFM	2.07	-0.77	6.12	1.072	0.901	
	CMM	2.14	-2.06	4.10	1.080	0.890	
	SMM	2.20	-2.05	4.70	1.053	0.882	0.502
	CRM	2.06	-1.23	3.98	1.067	0.911	0.453
	SRM	2.01	-0.89	5.10	1.119	0.929	
C1	CMM	1.33	1.77	10.61	0.864	0.986	0.347
	CFB	1.38	1.69	8.30	0.788	0.997	0.377
C2	CMF	1.02	3.63	6.27	0.987	0.935	0.406
	SMF	0.99	3.64	6.47	1.075	0.938	
	RMF	0.94	5.13	2.98	1.243	0.937	
	CFB	1.21	1.98	7.80	1.146	0.937	
	SFB	1.16	2.84	5.40	1.086	0.912	0.270
C3	CM	1.32	1.45	12.40	1.091	0.895	
	SM	1.43	1.13	11.92	1.076	0.848	0.337
	RM	1.58	0.20	8.77	1.058	0.841	0.305
	CB	1.27	1.06	9.77	1.091	0.959	0.186
	SB	1.42	0.41	9.35	1.049	0.936	0.182
L1	CM	0.42	10.86	12.09	1.166	1.080	
	SRM	0.54	8.69	9.50	1.155	1.041	
L2	CM	1.05	3.13	19.94	0.800	0.968	
	SRM	1.11	2.85	19.86	0.817	0.922	
L3	CM	1.19	2.52	20.39	0.758	1.001	
	CRM	1.27	1.26	19.36	0.816	0.975	
L4	CFM	2.15	-0.63	13.58	1.017	0.979	0.549
	SFM	2.24	-0.82	11.67	1.045	0.990	0.336
	CMM	2.32	-2.24	11.76	1.107	0.980	0.524
	SMM	2.36	-1.75	10.54	1.004	0.960	0.184
	CRM	2.32	-2.60	11.11	1.012	0.962	0.450
	SRM	2.33	-1.48	9.76	0.972	0.971	0.259
L5	CFM	1.06	2.84	11.41	0.921	0.853	0.516
	SMM	1.04	3.41	10.27	1.093	0.866	0.214
	CRM	1.08	2.29	8.36	1.020	0.905	0.252
L6	CFM	1.79	-0.93	13.72	0.850	1.015	0.303
	SMM	1.84	-0.07	13.35	0.845	1.030	0.136
	CRM	1.72	1.01	14.93	0.896	1.027	0.122
L7	CFM	1.94	-0.65	9.77	1.035	0.832	0.544
	SFM	1.95	-0.68	12.32	1.105	0.882	0.271
	CRM	2.04	-1.52	9.53	1.030	0.912	0.200
	SRM	2.17	-1.70	10.85	1.001	0.886	0.350
L8	CFM	0.50	9.20	11.15	1.360	0.828	
	SMM	0.64	7.84	9.26	1.298	0.962	
	RM	0.78	6.47	8.28	1.102	1.118	

Max	2.63	10.86	20.39	1.37	1.12	0.70
Min	0.42	-4.33	-2.93	0.76	0.81	0.11
Avg	1.63	0.95	4.96	1.04	0.93	0.34

Table D-3. Data of receiver architectural parameters for all receiver locations.

Room	Receiver	x ft.	|y| ft.	z ft.	r ft.	a degree	av degree	|ah| degree	rc ft.
O1	CFM	37.9	4.80	-4.8	38.5	11.7	-7.2	7.20	55.7
	SFM	32.6	29.60	-4.8	44.3	10.8	-6.2	42.20	54.5
	CMM	74.2	4.80	-2.3	74.4	7.3	-1.8	3.70	59.1
	SMM	69.6	30.60	-2.3	76.1	7.3	-1.7	23.70	58.3
	CRM	96.0	4.80	-0.2	96.1	5.6	-0.1	2.90	60.4
	SRM	92.4	30.20	-0.2	97.2	5.6	-0.1	18.10	10.7
	C1B	115.0	11.50	22.3	117.7	5.5	10.9	5.70	9.9
	S1B	81.2	44.60	14.1	93.7	11.6	8.7	28.80	9.3
	C2B	115.0	11.50	44.1	123.7	5.1	20.9	5.70	19.3
O2	CFM	48.0	5.80	-5.7	48.7	9.3	-6.7	6.90	56.9
	SFM	43.8	26.60	-5.7	51.5	8.9	-6.4	31.30	56.9
	CMM	75.0	6.30	-4.0	75.3	6.6	-3.0	4.80	55.6
	SMM	72.0	26.50	-4.0	76.8	6.5	-3.0	20.20	55.6
	CRM	110.6	4.40	-2.3	110.7	6.2	-1.2	2.30	5.5
	SRM	109.2	26.50	-2.3	112.3	6.2	-1.2	13.60	5.5
	B1B	58.6	33.50	8.8	68.0	10.7	7.4	29.80	5.0
	S1B	111.4	29.30	10.4	115.6	10.0	5.2	14.70	42.0
	C1B	116.2	5.80	10.4	116.8	7.7	5.1	2.90	42.0
	B2B	58.5	34.80	21.4	71.3	6.2	17.5	30.70	30.6
	S2B	122.7	30.30	23.0	128.4	11.4	10.3	13.90	29.1
	C2B	127.4	6.70	23.0	129.7	10.2	10.2	3.00	29.1
O3	CFM	33.5	6.00	-4.8	34.4	10.1	-8.0	10.20	42.7
	SFM	29.5	28.00	-4.8	41.0	8.8	-6.7	43.50	42.7
	CMM	66.0	6.00	-2.7	66.3	8.4	-2.3	5.20	43.0
	SMM	62.0	32.50	-2.7	70.1	8.2	-2.2	27.70	43.0
	CRM	86.0	6.00	-0.5	86.2	7.9	-0.3	4.00	8.3
	SRM	83.5	30.00	-0.5	88.7	7.8	-0.3	19.80	8.3
	FSRM	77.0	52.00	-0.5	92.9	7.8	-0.3	34.00	8.3
	CFB	88.5	9.00	17.7	90.7	7.8	11.3	5.80	22.7
	SFB	81.5	37.00	17.7	91.2	7.8	11.2	24.40	22.7
	CRB	117.0	6.00	28.1	120.5	9.5	13.5	2.90	11.5
	SRB	114.0	31.50	28.1	121.6	9.6	13.4	15.40	11.5
	FSRB	108.0	57.00	28.1	125.3	10.1	13.0	27.80	11.5
O4	CFM	37.7	9.60	-3.8	39.1	9.6	-5.6	14.30	49.1
	SFM	33.6	25.60	-3.8	42.4	9.2	-5.1	37.30	49.1
	CMM	54.4	9.60	-2.4	55.3	8.0	-2.5	10.00	56.2
	SMM	50.6	26.90	-2.4	57.3	7.9	-2.4	28.00	56.2
	CRM	78.4	9.60	1.2	79.0	7.2	0.9	7.00	52.8
	SRM	75.6	27.80	1.2	80.5	7.2	0.9	20.20	52.8
	CX	73.6	9.60	9.9	74.9		7.6	7.40	5.3
	SX	39.4	35.20	12.2	54.2		13.0	41.80	35.8
	CFB	73.6	7.00	25.6	78.3	3.4	19.1	5.40	19.3
	SFB	70.4	28.10	25.6	80.0	3.8	18.7	21.80	19.3
	CMB	101.8	7.00	37.4	108.7	2.4	20.1	3.90	19.5
	SMB	99.2	28.10	37.4	109.7	2.6	19.9	15.80	19.5
	CRB	123.2	7.00	46.6	131.9	1.9	20.7	3.30	11.3
	SRB	126.4	28.10	49.2	138.6	1.7	20.8	12.50	11.3
O5	CFM	32.0	4.60	-5.6	32.8	12.3	-9.8	8.20	54.1
	SFM	32.0	27.80	-5.6	42.8	10.0	-7.5	41.00	54.1
	CMM	57.7	4.60	-3.4	58.0	7.3	-3.4	4.60	54.3
	SMM	57.7	27.80	-3.4	64.1	7.0	-3.0	25.70	54.3
	CRM	83.6	4.60	-1.5	83.7	6.5	-1.0	3.10	54.1
	SRM	83.6	27.80	-1.5	88.1	6.5	-1.0	18.40	54.1
	CUB	109.2	4.60	1.3	109.3	6.8	0.7	2.40	53.9
	SUB	109.2	27.80	1.3	112.7	6.8	0.7	14.30	53.9
	C1B	119.2	3.70	14.1	120.1	6.1	6.7	1.80	6.7
	C2B	121.2	10.70	27.3	124.7	4.8	12.7	5.00	5.6
	S2B	55.3	41.00	22.4	72.4	0.2	18.0	36.60	6.7
	C3B	124.7	10.70	41.0	131.7	-0.1	18.1	4.90	12.7
O6	CFM	39.0	8.50	-5.3	40.3	7.5	-7.6	12.30	63.1
	SFM	37.0	19.00	-5.3	41.9	7.2	-7.3	27.20	62.6
	CMM	64.0	8.00	-3.8	64.6	10.3	-3.4	7.10	64.1
	SMM	56.5	33.00	-0.8	65.4	7.7	-0.7	30.30	9.1
	CRM	96.5	10.50	1.3	97.1	8.7	0.8	6.20	8.1
	SRM	90.5	23.00	1.3	93.4	8.1	0.8	14.30	8.1
	C1B	94.0	9.00	16.3	95.8	12.8	9.8	5.50	8.1
	S1B	55.5	35.00	14.3	67.1	8.4	12.3	32.20	10.1
	C2B	97.0	8.00	32.8	102.7	10.5	18.6	4.70	8.1
	S2B	56.5	31.00	30.8	71.4	7.1	25.6	28.80	10.1
	C3B	95.5	8.00	47.3	106.8	10.2	26.3	4.80	11.1
	S3B	66.0	37.00	46.3	88.7	6.7	31.5	29.30	12.1
O7	CFM	28.8	4.80	-4.6	29.5	11.4	-9.0	9.40	51.8
	SFM	24.2	25.50	-4.6	35.5	9.9	-7.5	46.50	51.8
	CRM	53.8	6.80	-3.3	54.3	8.0	-3.5	7.20	53.3
	SRM	49.0	29.50	-3.3	57.3	7.8	-3.3	31.00	53.3
	CX	64.5	11.30	9.4	66.1		8.2	9.90	4.1
	SX	44.0	36.00	8.9	57.5		8.9	39.30	4.1
	CFB	71.2	9.00	24.4	75.8	5.0	18.8	7.20	30.8
	SFB	64.5	30.30	24.2	75.2	5.1	18.8	25.10	30.8
	CMB	98.0	5.80	36.2	104.6	3.6	20.3	3.40	21.8

Table D-3. (Continued).

Room	Receiver	x ft.	|y| ft.	z ft.	r ft.	a degree	av degree	|ah| degree	rc ft.
	SMB	95.5	28.50	36.2	106.0	3.9	20.0	16.60	21.8
	CRB	114.0	5.80	44.4	122.5	2.5	21.3	2.90	8.3
	SRB	110.8	30.50	44.4	123.2	2.7	21.1	15.40	8.3
O8	CFM	27.5	4.00	-5.0	28.2	12.2	-10.2	8.30	57.3
	SFM	25.0	20.00	-5.0	32.4	10.9	-8.9	38.70	57.8
	CMM	48.0	2.00	-4.0	48.2	7.7	-4.8	2.40	56.7
	SMM	46.0	24.00	-2.9	52.0	6.2	-3.2	27.60	55.8
	CRM	70.0	2.00	-1.9	70.1	10.5	-1.6	1.60	54.0
	SRM	62.0	23.00	-1.9	66.2	10.6	-1.6	20.40	54.0
	C1B	78.5	2.00	10.4	79.2	10.6	7.5	1.50	40.8
	S1B	76.8	23.00	9.8	80.8	11.1	7.0	16.70	41.4
	C2B	81.6	2.00	29.4	86.7	9.9	19.8	1.40	22.8
M1	CMF	50.0	7.20	-1.9	50.6	8.3	-2.2	8.20	55.7
	SMF	45.2	31.40	-1.9	55.1	8.2	-2.0	34.80	48.6
	RMF	83.6	12.40	2.8	84.6	7.1	1.9	8.40	72.3
	C1B	98.6	9.10	17.0	110.5	8.4	9.7	5.30	6.8
	M1B	71.4	37.40	12.9	81.6	9.1	9.1	27.60	7.6
	S1B	30.2	45.60	9.3	55.5		9.7	56.50	6.7
	B3C	112.0	9.10	50.3	123.1	2.4	24.1	4.60	9.9
	M3B	81.2	45.20	41.3	101.7	2.5	24.0	29.10	13.9
	F3B	29.7	46.60	31.5	63.6		29.7	57.50	13.3
M2	CFM	32.3	5.60	-5.3	33.2	11.2	-9.2	9.80	53.9
	SFM	29.1	19.20	-5.3	35.3	10.6	-8.6	33.40	45.9
	CMM	56.6	6.40	-4.5	57.2	8.0	-4.5	6.50	12.4
	SMM	48.8	36.80	-4.5	61.2	7.7	-4.2	37.00	12.4
	CRM	80.9	6.40	-2.7	81.2	7.4	-1.9	4.50	9.6
	SRM	74.9	37.90	-2.7	84.0	7.3	-1.8	26.90	9.6
	CFB	54.0	3.60	17.6	56.9	7.0	18.0	3.80	31.6
	SFB	45.1	31.20	17.6	57.6	7.2	17.8	34.70	31.6
	CMB	76.8	3.60	29.1	82.2	4.3	20.7	2.60	19.4
	SMB	70.4	36.20	29.1	84.3	4.8	20.2	27.20	19.4
	CRB	111.4	3.60	45.3	120.3	2.9	22.1	1.80	10.4
	SRB	107.2	36.20	45.3	121.9	3.2	21.8	18.70	10.4
M3	CFM	57.3	11.50	1.0	58.4	12.0	1.0	11.40	36.6
	SFM	51.5	33.80	1.0	61.6	12.1	0.9	33.20	32.8
	CMM	78.0	11.50	5.0	79.0	10.9	3.6	8.40	33.1
	SMM	70.3	42.80	5.0	82.4	11.0	3.5	31.30	36.1
	CRM	109.0	11.50	14.3	110.5	8.9	7.4	6.00	17.6
	SRM	97.8	56.30	14.3	113.7	9.1	7.2	29.90	22.3
C1	CMM	34.6	4.50	-4.0	35.1	6.6	-6.5	7.40	30.1
	CFB	73.2	3.30	7.9	73.7	11.2	6.2	2.60	19.5
C2	CMF	21.7	5.30	-3.9	22.7	10.0	-9.9	13.70	28.7
	SMF	14.8	22.50	-3.9	27.2	8.3	-8.2	56.70	17.1
	RMF	36.0	14.50	-3.9	39.0	5.8	-5.7	21.90	4.0
	CFB	37.0	8.30	6.5	38.5	2.8	9.7	12.60	6.6
	SFB	13.2	39.40	6.5	42.1	3.6	8.9	71.50	6.6
C3	CM	23.7	6.20	-4.2	24.9	9.8	-9.7	14.70	27.1
	SM	18.8	34.00	-4.2	39.1	6.2	-6.2	61.10	20.9
	RM	35.5	15.50	-4.2	39.0	6.2	-6.2	23.60	25.1
	CB	47.5	7.10	7.9	48.7	4.3	9.3	8.50	4.3
	SB	34.7	33.20	7.9	48.7	4.3	9.3	43.70	9.1
L1	CM	21.8	1.50	-1.5	21.9	9.0	-3.9	3.90	7.5
	SRM	35.3	1.50	-0.7	35.3	6.2	-1.1	2.40	6.4
L2	CM	8.0	2.00	-1.8	8.4	12.5	-12.3	14.00	4.8
	SRM	18.0	8.00	-1.8	19.8	5.3	-5.2	24.00	4.8
L3	CM	8.0	2.00	-1.8	9.9	12.5	-12.3	14.00	7.9
	CRM	19.0	8.00	-1.8	20.6	5.1	-5.0	22.80	7.9
L4	CFM	30.5	5.50	-3.5	31.8	9.5	-6.4	10.20	17.6
	SFM	28.3	30.50	-3.5	42.0	7.8	-4.8	47.10	17.6
	CMM	54.0	5.50	-2.0	54.6	8.1	-2.1	5.80	14.8
	SMM	51.7	30.50	-2.0	60.1	7.9	-1.9	30.50	14.8
	CRM	77.5	5.50	6.1	77.7	5.0	4.5	4.10	10.6
	SRM	75.0	30.50	6.1	81.0	5.2	4.3	22.10	10.6
L5	CFM	26.0	4.50	0.7	26.4	7.3	1.5	9.80	10.1
	SMM	34.0	20.00	2.2	39.5	5.7	3.2	30.50	8.6
	CRM	46.5	6.00	3.7	47.0	4.3	4.5	7.40	7.1
L6	CFM	15.5	1.80	-3.1	15.9	11.3	-11.2	6.60	13.2
	SMM	23.5	10.30	-2.2	25.8	11.5	-4.9	23.70	11.0
	CRM	30.1	3.50	-1.5	30.3	10.7	-2.8	6.60	9.6
L7	CFM	18.1	3.80	-1.7	19.3	5.3	-5.3	11.90	13.0
	SFM	13.3	18.40	-1.7	22.9	4.4	-4.3	54.10	12.1
	CRM	35.0	6.00	0.4	35.7	6.9	0.6	9.70	12.8
	SRM	25.4	30.20	0.4	39.5	7.0	0.6	49.90	12.2
L8	CFM	15.8	1.20	-1.8	16.0	6.6	-6.5	4.30	9.4
	SMM	22.8	12.40	-1.8	26.0	4.0	-4.0	28.50	9.4
	RM	36.8	12.50	1.5	38.9	7.8	2.2	23.90	6.1

Max	127.4	57.0	50.3	138.6	12.8	31.5	71.5	72.3
Min	8.0	1.2	-5.7	8.4	-0.1	-12.3	1.4	4.0
Avg	63.7	5.0	8.6	69.8	7.5	4.0	18.1	26.6

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BIOGRAPHICAL SKETCH

Wei-hwa Chiang was born on December 24, 1962, in Taipei, R.O.C. In his early years, he enjoyed being exposed to all kinds of new knowledge around him. He started studying the violin at the age of eight and continued his musical study for many years. He entered college majoring in architecture, hoping to pursue a profession in which he could fully devote himself . His interests in geometry, physics, drafting, and crafts during high school led him to make that choice.

Before he came to the U.S.A. to pursue his master's degree, he had no idea that he would be specializing in architectural acoustics. One of his classmates, Richard Brooksfield, showed him the acoustics laboratory which was run by Professor Siebein. He realized the opportunity to join together his two best interests, architecture and music. He took this opportunity and stayed on for almost six years.

Studying in the U.S.A., however, kept him away from his family. Upon graduation, he returned to his native country and devoted himself to the research and practice of architectural acoustics.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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